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TRW

DEVELOPMENT OF A HELIOTROPIC ORIENTATION DEVICE FOR HIGH CONCENTRATION RATIO SOLAR POWER GENERATION SYSTEMS

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QUARTERLY TECHNICAL PROGRESS REPORT
15 January 1964 – 15 April 1964

Prepared for
NASA Langley Research Center
Langley Station
Hampton, Virginia 23365

Prepared Under
CONTRACT No.: NAS 1-3588
CONTROL No.: L 3312

TRW ELECTROMECHANICAL DIVISION
THOMPSON RAMO WOOLDRIDGE INC.
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APRIL 21, 1964

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By the
SOLAR ENERGY SYSTEMS GROUP
NEW PRODUCT RESEARCH DEPT.

TRW ELECTROMECHANICAL DIVISION
THOMPSON RAMO WOOLDRIDGE INC.
CLEVELAND, OHIO

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1.0 INTRODUCTION

Recent advances have made thermionic power conversion systems extremely desirable for space vehicle applications, particularly when high precision solar concentrators use the limitless energy of the sun to provide the required power. The advantages of not having to carry a fuel or heat source are obvious, but the requirement for high temperatures in thermionics fosters a formidable orientation problem. The requirement that high precision concentrators be sun oriented to within tenths of a degree establishes the need for development of highly accurate and reliable orientation mechanisms.

Feasibility test models previously designed and built by TRW have shown that heliotropic mounts can provide the type of control action required to orient solar concentrators without using complex electronic or electromechanical devices. The TRW models demonstrated that mount power requirements are very small, representing only the energy normally lost outside a thermionic generator cavity due to the image spread associated with large diameter reflectors. The simplicity of the design concept and the small number of parts in a heliotropic mount promote high performance and reliability.

While some systems aspects may vary greatly depending on the mission, one requirement is common to all missions using solar energy for power - the collector must be oriented toward the sun with a minimum expenditure of fuel or energy and a minimum of complexity in the attitude control mechanism. Development and incorporation of the heliotropic mount conceived by TRW would greatly ease many of the problems associated with space vehicles utilizing sun-powered generation systems. Because the orientation requirements of the solar concentrators may exceed those for any other component, a considerable savings in control mechanism and fuel may be realized if the vehicle attitude limits can be expanded to plus or minus five degrees instead of the 1/10 or 2/10 degree required by the concentrators. Also, many solar generator concepts will involve the use of relatively small concentrator-generator modules. The heliotropic mount represents an ideal way of easing the structural alignment tolerances in the assembly of an array of modules since each module is independently oriented.

The heliotropic mount is a sun sensing and seeking device as is implied by its name. In practice it is possible to arrange many simple mechanisms, exclusive of any electronics or electromechanical components, which will exhibit a tropistic reaction when placed in view of the sun. TRW has attempted to select the most promising mechanisms for study and evaluation. The TRW application of the heliotropic mount concept is illustrated in Figure 1.1 for a mechanism using bimetallic strips to obtain the corrective action. The motion shown for the misaligned concentrator is greatly exaggerated since the mount mechanism can be made to be a very high gain device. The operating principle is however clearly illustrated. As the vehicle, and therefore, the concentrator, is misoriented with respect to the sun the focal spot tends to move away from the concentrator axis and produce an unbalanced heating of the interposed bimetallic elements. These elements in turn produce an appropriate restoring torque which minimizes the alignment error.

HELIOTROPIC ORIENTATION SYSTEM SCHEMATIC

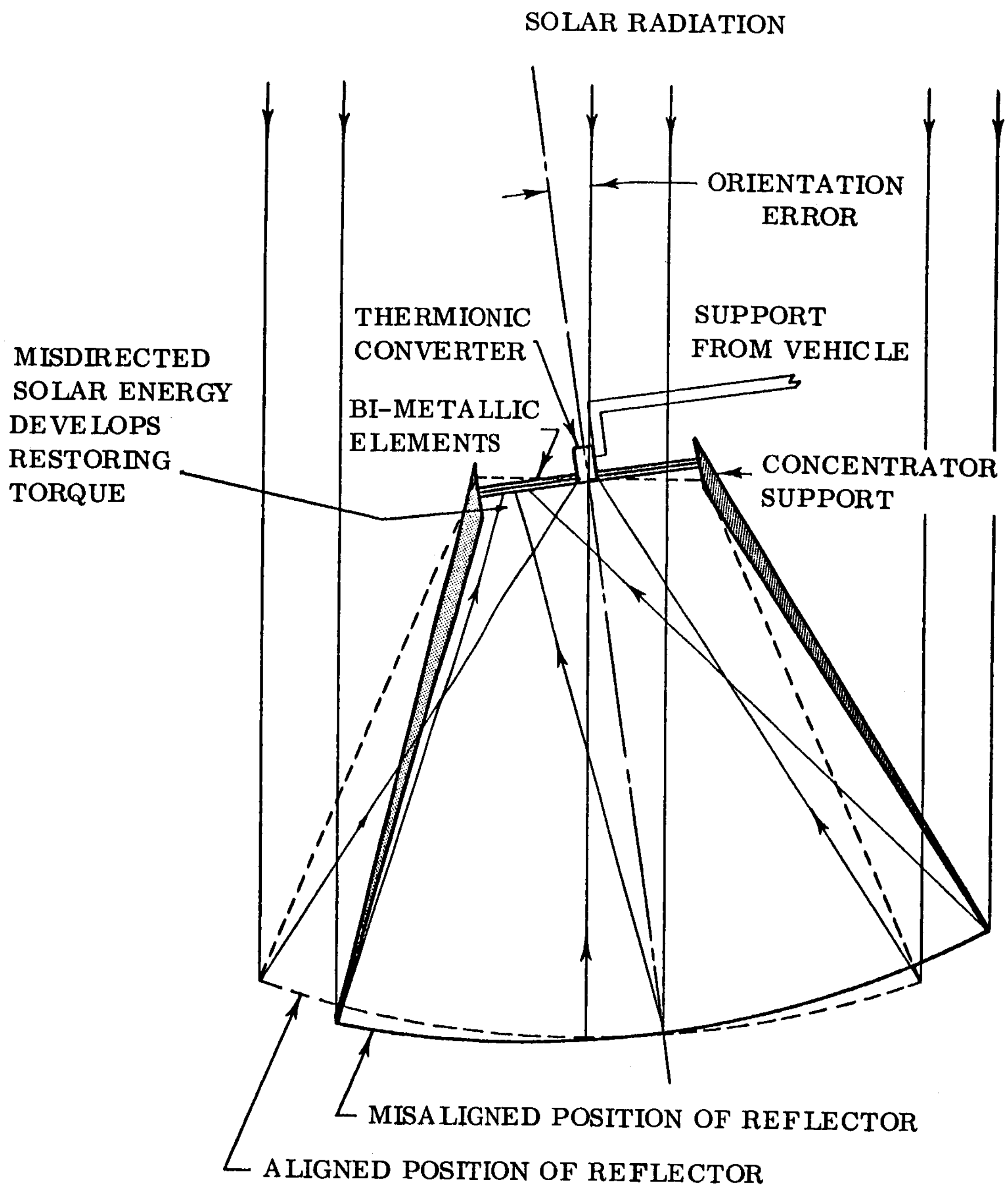


FIGURE 1.1

In early 1959 TRW designed and tested several feasibility models of the heliotropic mount which used simple bimetallic sensor actuators to obtain concentrator alignment corrections. An improved model shown in Figure 1-2 was tested and found to possess a gain sufficient to limit concentrator alignment error to less than 0.1 degrees in the face of vehicle misorientation of up to 5 degrees. Other characteristics such as thermal response, mechanical strength or stiffness, and load capacity were somewhat deficient.

Under the present NASA sponsored program the objective is to develop a practical mount configuration which will operate with precision concentrators of up to 10 feet in diameter. The test mount design however is sized to operate with a 5 foot concentrator to facilitate testing of mount performance under solar operation. During the course of this program TRW reviewed several mount concepts and based on the results of this review selected and carried out a specific concept and a detailed mount design. This design is as near prototype as possible and demonstrates that the selected configuration is entirely compatible with the operating environment and possesses operating characteristics suitable for integration in future space power systems. The mount design will be completely tested to determine all pertinent thermal, mechanical, and structural characteristics. Because of the nature of the tests and the complications of trying to simulate space vacuums, zero gravity conditions, thermal equilibriums, etc. the test activity represents one of the most critical and difficult undertakings in this program.

There are a number of configurations using both bimetallic and vapor pressure approaches which can be adapted to a solar power generating system to reduce orientation requirements by means of the concentrator positioning technique. The principle configurations which were considered in detail under this program are reviewed in the following sections. In all cases the mount sensors were considered to intercept the fringe flux at the generator cavity aperture. Other approaches using secondary lenses or mirrors are available and perhaps very applicable since one of the major problems is to prevent mount or sensor destruction during initial acquisition or gross misorientation periods when very high flux levels are felt at the sensors. The use of the concentrated cone of flux is very desirable however since it provides for a very high and variable gain system and eliminates the problems of aligning the secondary mirrors with the axis of the primary concentrator.

COMPLETE HELIOTROPIC MOUNT ASSEMBLY
INSTALLED ON A VACUUM PLATE

FIGURE 1.2

2.0 SUMMARY

The effort during the past three months has been directed in three major areas associated with the development of a near prototype heliotropic mount. These areas are:

1. The review of the basic considerations and design factors related to the many mount and actuation concepts
2. A detailed study of, and finalization of a preferred mount design concept, and
3. The fabrication of all mount hardware along with the preparation of the test facilities required for a comprehensive mount evaluation.

A review of the approaches to reorientation of misaligned solar concentrators has led to the conclusion that the most satisfactory was is to slew or rotate the concentrator about the generator assembly. Other approaches suffer excessive losses and are generally more difficult to mechanize. The basic heliotropic mechanisms including various configurations of bimetallic elements and several vapor pressure mechanisms using bellows, bourdon tubes, and helix configurations were evaluated on the basis of their particular characteristics and limitations. The results of this evaluation has led to the selection of the vapor pressure concept using bellows type actuators, mercury as the charging fluid, and flexure bearings as the prime components. This selection was made not because bimetallic and other vapor pressure concepts were unsuitable, but because the bellow actuator concept appears to offer the best combination of desirable characteristics and the greatest flexibility and adaptability which will be required in future system applications.

A tentative design was carried out using the bellows concept built around a thermionic type module consisting of a five foot diameter solar concentrator and a 100 watt thermionic generator. Appropriate characteristics were assumed for the concentrator, generator and mount hardware. These characteristics were then used in an analog computer program to permit a reasonably comprehensive study of the mount performance. Favorable computer study results including a parametric evaluation of various changes in component characteristics were subsequently obtained. Based on these results a prototype heliotropic mount was designed and the necessary drawings prepared.

The fabrication of a power distribution calorimeter which simulates the thermionic generator, the special mounting plates and bracketry, and the components of the heliotropic mount has been completed. The calorimeter device is intended to provide a good simulation of the operational environment associated with a thermionic generator and to serve as the power absorbing and measuring device required for the solar testing phase of the mount evaluations. The actual mount hardware is designed as an attachment to the calorimeter assembly and is designed to possess all the features which would be required for a working space power system. The complete assembly including the vacuum enclosures and support structures have been designed to permit a complete test evaluation of all thermal, dynamic, and mechanical mount characteristics.

3.0 MOUNT CONCEPT EVALUATION

3.1 Review of Methods for Correcting for Concentrator Misalignment

An evaluation of two proposed methods of concentrator and cavity alignment has been performed. These methods include generator cavity translation and concentrator realignment by means of heliotropic devices.

Of the two approaches stated a stronger case may be made for the concept which slews or repositions the concentrator. The arguments which are presented for or against each concept in this report are founded not only on an analytical evaluation but also upon practical physical and dynamic considerations appropriate to the mount mechanisms. The emphasis which is placed in these several areas is well founded in TRW's experience in all aspects of solar concentrator technology and the design and operational needs of thermionic and thermoelectric type generators. Other factors which are given consideration are those pertaining to the environmental and operating conditions which are present in the typical space station or vehicle.

The use of a mount arrangement which repositions the cavity in the focal plane to compensate for concentrator misalignment has been considered in detail. The chief advantage of such an arrangement is that it would not be burdened by the large inertias associated with the concentrator slewing mechanisms. Also by the addition of a small weight penalty it appears reasonable that such a mount could be made to withstand the spin loading associated with large rotating space vehicles or stations.

However, the flux distribution with this mount arrangement is subject to considerable distortion and spread due to angular misalignments in the concentrator. This is shown in the results of a computer program made by TRW on a 45 degree rim angle, ten foot diameter parabolic concentrator. The spot shape and axial displacement for the parabola under several conditions of misorientation is shown in Figure 3.1-1. The circular spot represents the aperture diameter which would be sufficient to intercept all of the solar flux assuming a perfect concentrator surface and geometry. The spot outlines shown displaced from this circular aperture represent the effect of misorienting this concentrator in the amount of 3, 10, and 30 minutes of arc. It is immediately seen that even if the cavity aperture were moved to coincide with the center of the peak flux intensity of each spot there would be substantial losses due to the large proportion of flux falling outside the aperture. The area of the spot with 30 minutes misorientation is 175 per cent of the circular aperture area. This number is substantially increased for orientation errors approaching 5 degrees and for concentrators of higher rim angles.

The translation requirements for a 60 inch concentrator with a 26 inch focal length and 60 degree rim angle would be approximately

$$\delta = 26 \sin \phi = 2.06 \text{ inches}$$

FOCAL SPOT DISTORTION DUE TO CONCENTRATOR ALIGNMENT ERRORS

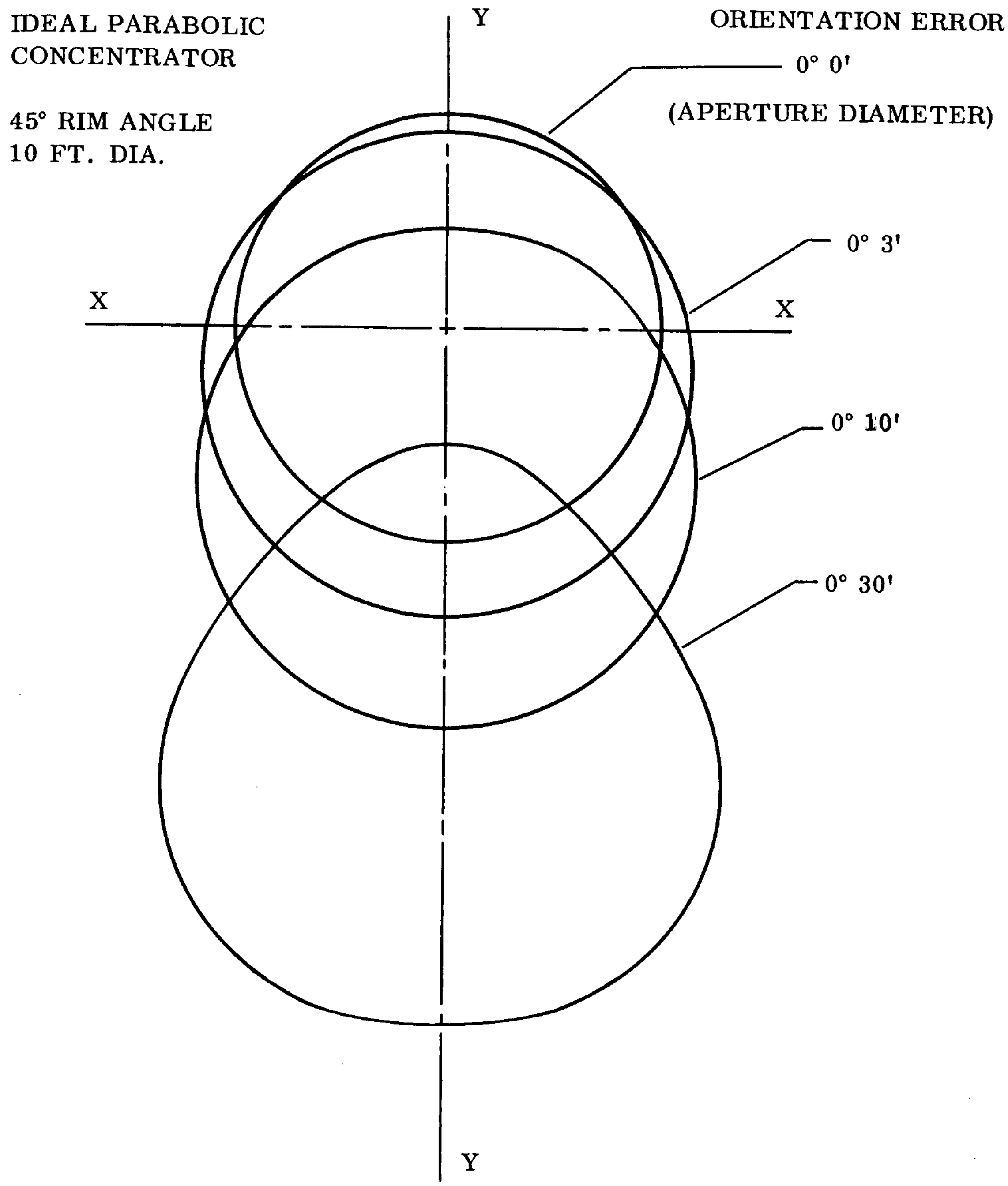


FIGURE 3.1-1

for Ø equal to 5 degrees. If the alignment error occurs on a plane 45 degrees from the actuator axis the required actuator stroke must be 2.92 inches. These numbers assume the ray from the center of the concentrator will be coincident with the center line of the altered flux distribution profile. Since this is not the case the actuator motion must be even larger. In considering motions of this sort it is almost mandatory that pistons, linear motor, jack screws, or similar components be utilized. Even if high flexure welded bellows could be employed the bulb sensor inventory volumes would become very large with an attendant loss in response and performance.

The fact that the focal spot is changed and the flux profile made unsymmetrical would also make it very difficult to determine a suitable sensor location. Even though the sensors would always seek a location where a force balance would exist in the mount actuator system the power input to the sensors would vary with misorientation error. This power input variation could easily be as much as 10 or 20 times the design value under oriented conditions and a mount failure due to overtemperature or overpressure might occur.

Because of the large amounts of power lost outside a properly sized cavity aperture, the excessively long actuator stroke requirements and the sensor location and equilibrium problems with angular misorientation it appears the translation type mount is unsatisfactory. Later, consideration of the concentrator alignment concept will show that in most respects the translation type mount is inferior.

The approach to concentrator reorientation which uses concentrator alignment must be considered in light of three factors. The first is the amount of power lost due to the rotation of the cavity aperture in the focal plane as part of the correcting action of the mount. The second is the variation in the spot shape, location and percentage power loss due to concentrator alignment error. The last factor is the effect on sensor power input due to spot changes with concentrator misorientation.

The amount of cavity power lost due to a rotation of the aperture plane relative to the concentrator axis has been found negligible compared to other spot distortion or translation losses. The analysis performed to establish the extent of this loss involves several simplifying assumptions. These are: 1) that the concentrator is perfectly aligned with the run, 2) the concentrator is a perfect parabola, and 3) the flux distribution is uniform over the focal spot.

With these assumptions it may be shown that the percentage of flux which fall outside the aperture circle for a single ray may be as high as 7.86 per cent. Figure 3.1-2 illustrates this prospect where y is the aperture circle radius established by the ellipse formed due to a solar angle of 32 minutes and a concentrator rim angle of 60 degrees.

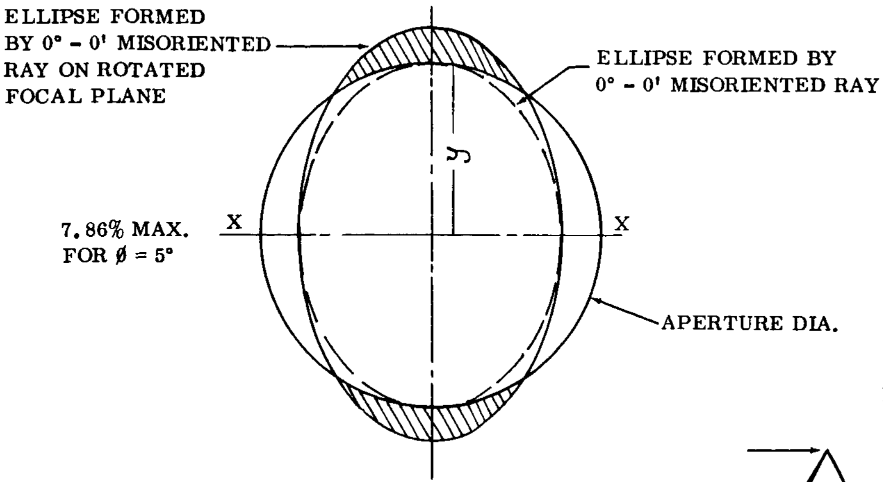


FIGURE 3.1-2

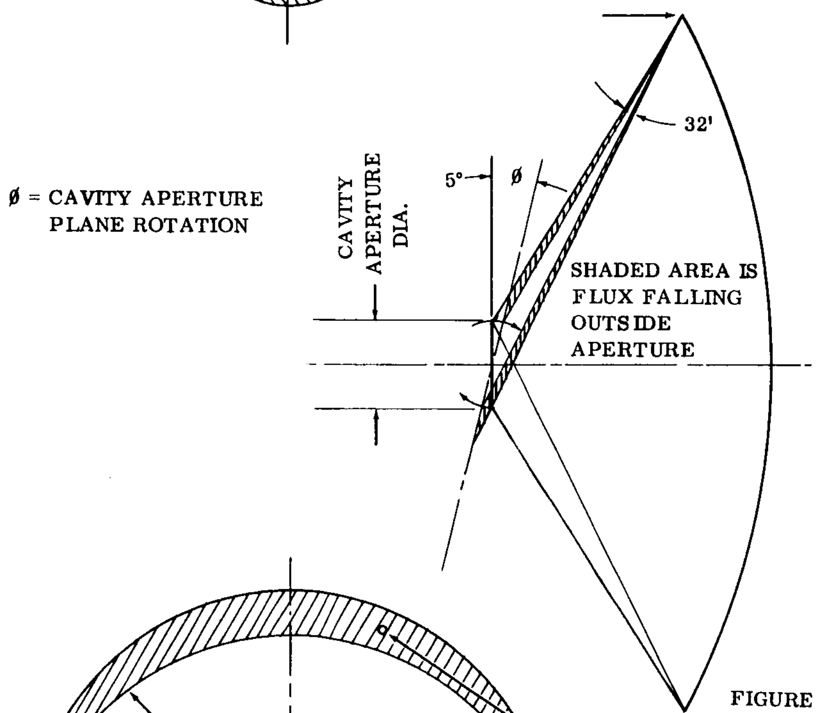


FIGURE 3.1-3

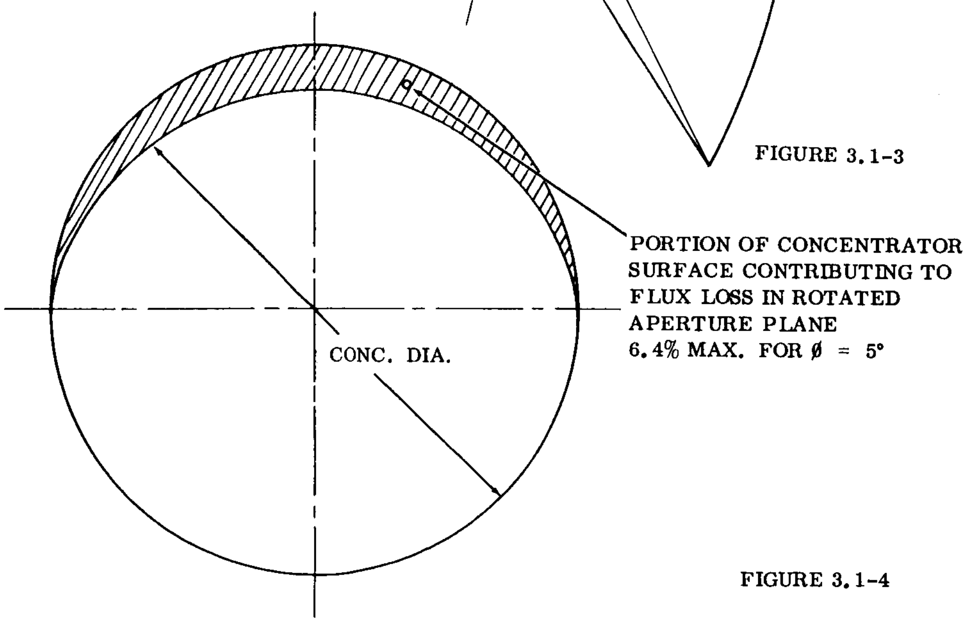


FIGURE 3.1-4

Examination of Figure 3.1-3 which represents the concentrator-cavity relationship shows at once that only part of the elongated ellipse will fall outside of the cavity. This part of the ellipse possesses an area sufficient to produce a 7.86 per cent reduction in cavity power based on a uniform flux distribution.

This percentage loss is only true for a ray coming from the edge of the rim at a point in the plane perpendicular to x-x and on the concentrator axis. All other rays would be subject to lesser or in most cases zero loss. An analysis of the concentrator geometry with respect to the inclined cavity aperture was made to determine what concentrator areas would actually cause ellipses with dimensions sufficient to produce an impingement of flux outside the cavity aperture limits. The results yield an effective concentrator area of 6.4 per cent and include a section of surface approximately as shown in Figure 3.1-4.

With a uniform flux distribution the total loss is then 7.86 x 6.4 or 0.503 per cent. With a true non-uniform flux distribution this percentage will drop by an estimated factor of ten or more. This loss representing a small fraction of one per cent can be safely neglected.

The power lost due to concentrator alignment error has been determined for a ten foot diameter concentrator and 45 degree rim angle using Figure 3.1-1. For a perfect parabola the change in shape and location of the spot relative to a cavity aperture located on the concentrator axis is seen to be great for misorientation errors in excess of 3 minutes. A higher rim angle would of course increase these changes in shape and location. Assuming uniform flux over the spot areas an integration has been performed to develop a curve of cavity power versus misorientation angle as shown in Figure 3.1-5. In a curve which would be generated using a true flux profile for each spot the shape would be altered to maintain the total power at a higher level for misorientation angles up to 16 minutes and reduce total cavity power at a much faster rate for angles exceeding 16 minutes.

A more general evaluation of the effects of concentrator misorientation may be had from the plot of results of another recent TRW computer study. Figure 3.1-6 shows the reduction in percentage of focal plane power which results for several assumed concentration ratios as a function of orientation error. The curve expressed for the 12,000 concentration ratio would be most appropriate for consideration with heliotropic devices. For this surve it is shown that even with the absence of concentrator surface and geometry errors the available power falls by 10% or more with an alignment error of 12 minutes. For most space power generation systems a 10 per cent decline in power would probably represent a tolerable limit.

Figure 3.1-7 represents a third evaluation of the effect of concentrator misorientation in terms of the measured power output from a thermionic cubical cavity generator as a function of concentrator orientation error. These curves and the results of other TRW solar tests of this generator are summarized in Figure 3.1-8. The band width is shown here to indicate the maximum variation in power output as a function of misorientation in several planes and with minor variations in the solar constant.

CAVITY POWER EFFICIENCY VERSUS MISORIENTATION

45° 10 Foot Diameter Concentrator Assuming Uniform Flux Distribution

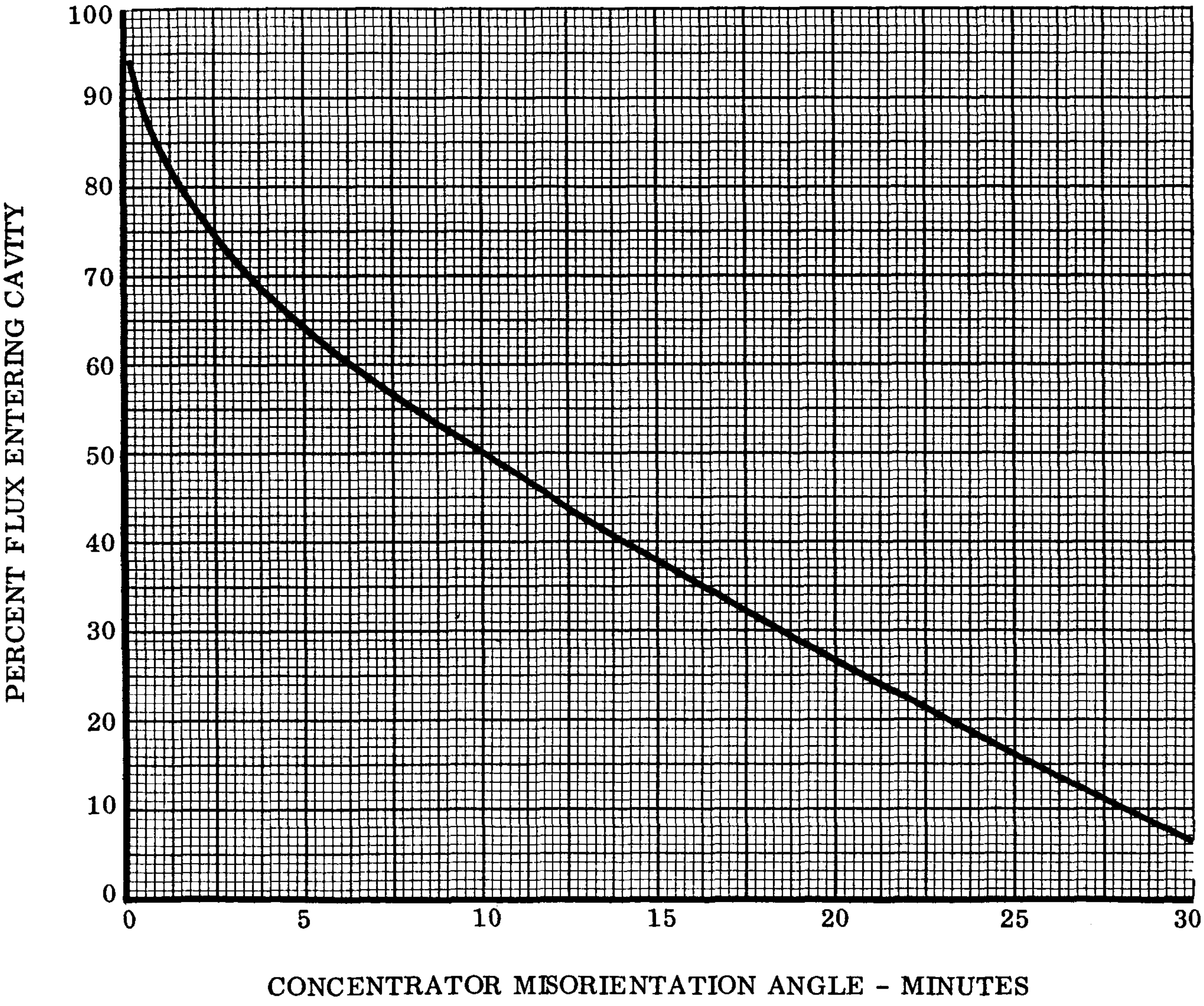


FIGURE 3.1-5

PER CENT ENERGY FALLING INTO APERTURE VS. CONCENTRATION RATIO

(Computed From Generalized Mathematical Model on IBM 7090)

Rim Angle = 60°

$\delta_R = \delta_\theta = 0$

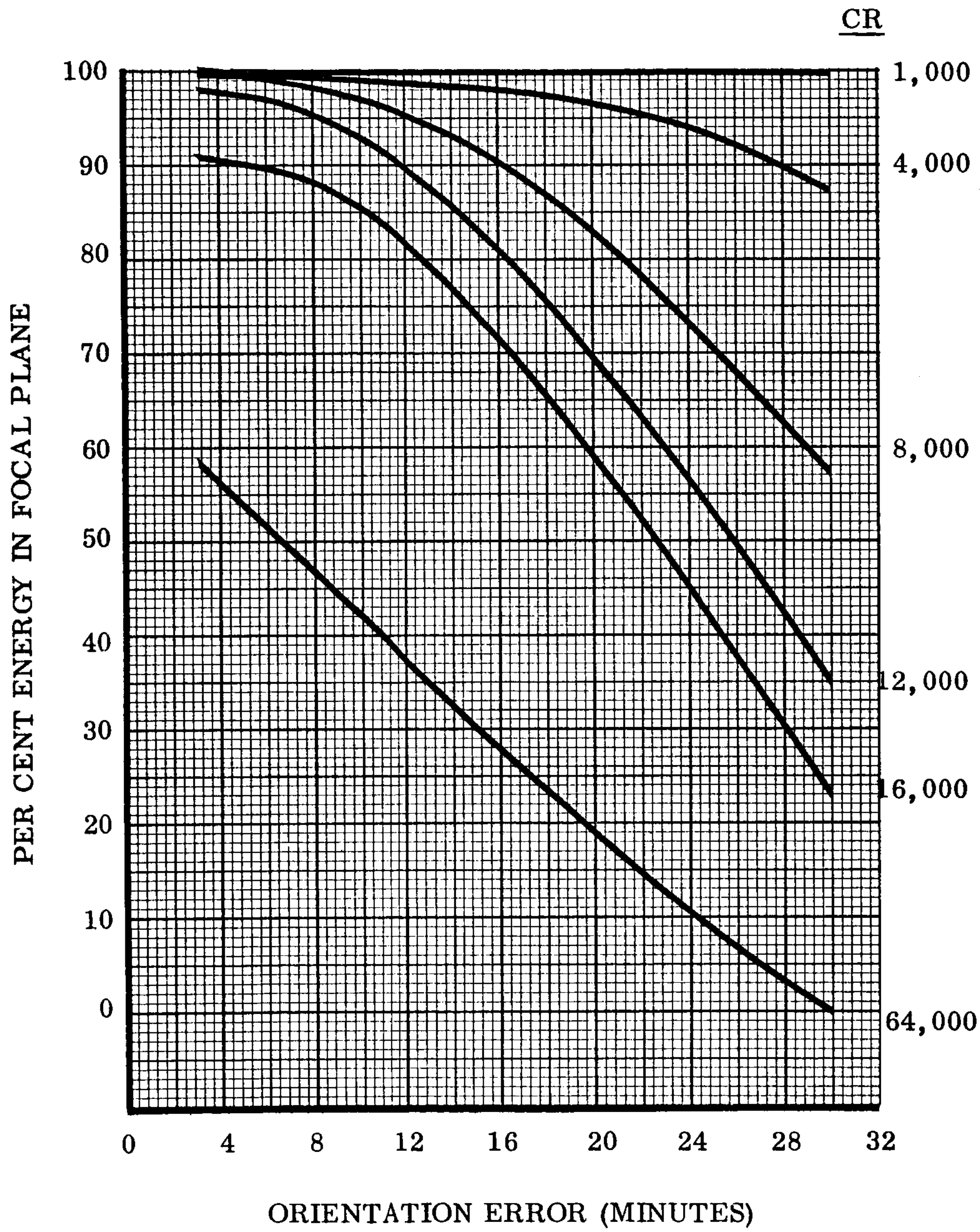
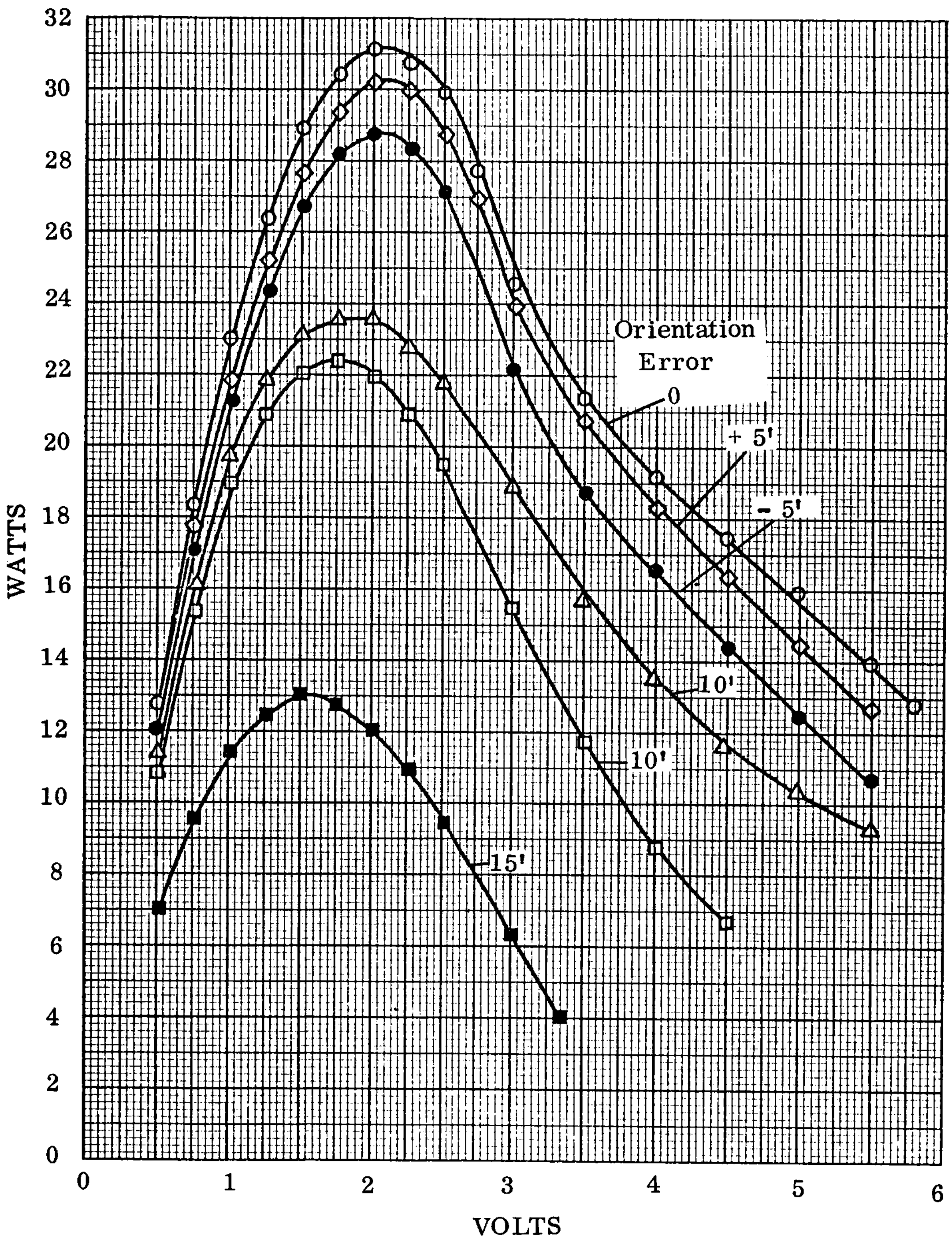
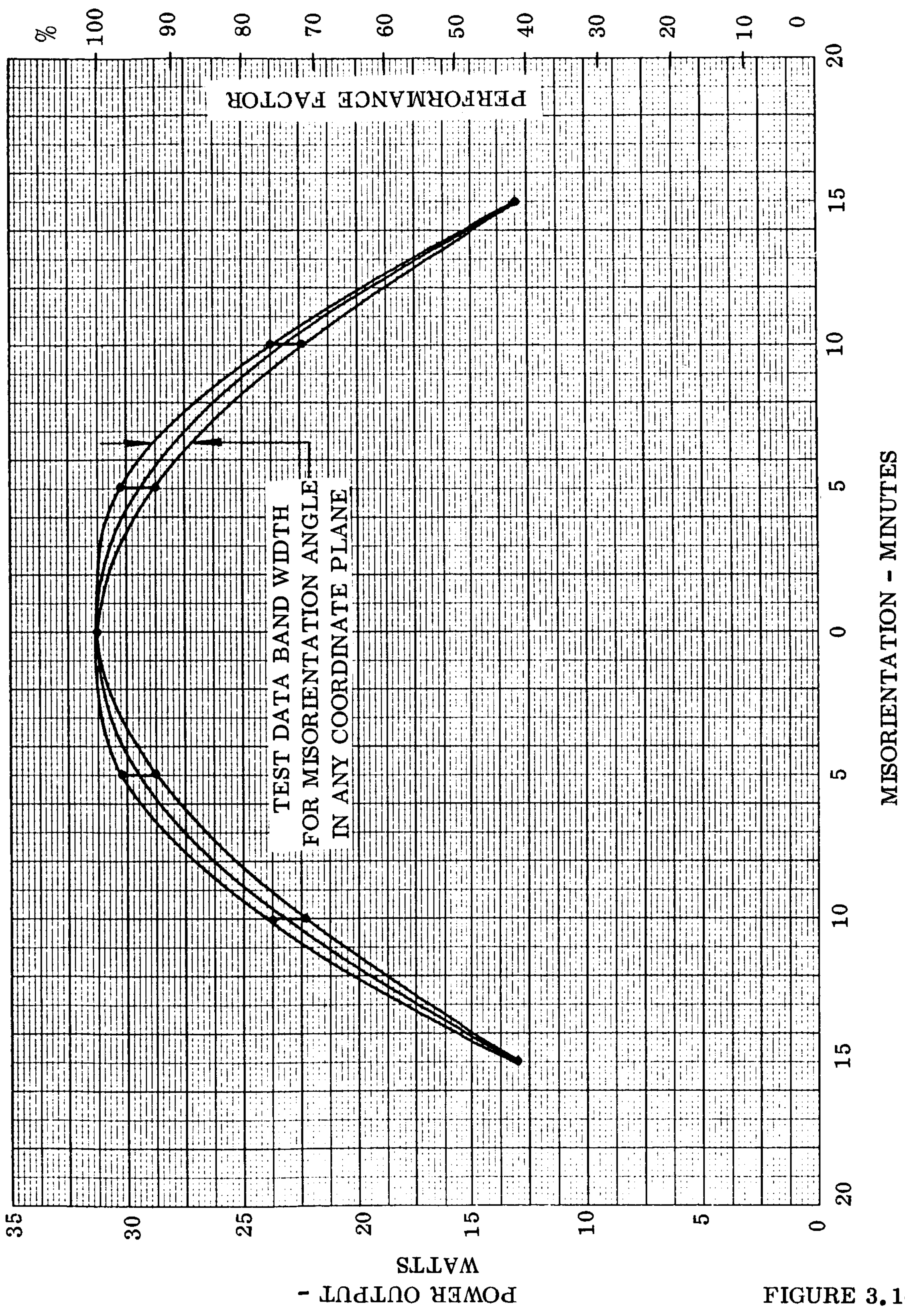


FIGURE 3.1-6



POWER OUTPUT VERSUS VOLTAGE FOR VARIOUS SOLAR CONCENTRATOR MISORIENTATION ANGLES

FIGURE 3.1-7



COMPOSITE PLOT OF MISORIENTATION EFFECTS - C. C. G.
(POWER & PERFORMANCE FACTOR VERSUS MISORIENTATION ANGLE)

FIGURE 3.1-8

The amount of power attenuation here indicates not only the effect of a reduction in cavity power but the effect of a change in generator performance due to a less favorable flux distribution and a reduction in generator efficiency due to the cavity temperature fall off. This data is also of particular interest in the current heliotropic program because it also includes the deterioration in performance which is due to the pyrex glass dome which caps the environmental test chamber. With the calorimeter device used to simulate a thermionic generator for the mount hardware it will be possible to generate a similar composite curve. The new curve when related to Figure 3.1-8 should permit a separation of the influence of concentrator alignment and generator efficiency reduction due to temperature fall off.

It is expected that even though the cavity power will not drop as rapidly with alignment error as is shown in Figure 3.1-7, the fall off will be rapid enough to require a reduction in permissible mount error from 12 minutes to perhaps 6 minutes to insure a reasonable consistency in cavity power input.

The last factor concerning power input variations to the sensors due to changes in the spot shape and flux distribution is the most difficult to evaluate. The misorientation of the concentrator, even when limited to 12 minutes, results in a general enlargement of the spot and a distortion of the flux profile. The sensors will not introduce any additional alignment errors due to this change or distortion in the signal source. In fact the balancing action of the mount is such as to insure the direction of the maximum possible flux into the cavity under any condition of misalignment regardless of the type or extent of spot or flux distortion. This is true because regardless of the flux profile or ambient level of the sensors, the actuation mechanism will always try to reduce the sensor power input to a minimum. Also for a balanced system each sensor in an opposing pair will be adjusted to have a comparable minimum input which requires therefore that the maximum flux be directed between these sensing points. Since the sensing points are located at the cavity aperture the flux must enter the cavity. The only real danger is that the increase in power input might raise the ambient sensor temperature and cause the destruction of the mount mechanism. It is felt an attempt at analyzing this area would be meaningless. The ultimate proof of the mount capability to adjust to such spot deformations will require the completion of the solar test phase of this program. If no serious difficulties are encountered in the solar tests it may be safely assumed the mount could be adapted to any other concentrator-generator assembly.

3.2 Review of Bimetallic Mechanisms

The most direct approach and the one which has been used in several TRW feasibility test mounts uses simple bimetallic sensor actuators. The previously tested models utilized these bimetals in the form of simple cantilever members with the tips protruding into the cone of concentrated solar flux and the rear end anchored to a gimbal ring arrangement. The operating mechanism involved the tilting of this gimbal ring by the unbalanced heating of opposing bimetal elements. These mounts worked well in most respects but possessed several weaknesses and performance limitations.

For example such arrangements require some means of supporting or fixing the tip end to the generator assembly without introducing large resisting torques in the plane 90 degrees removed which would render the elements in that plane inoperative. Also there was found to exist a conflict between requirements for mechanical stiffness and rapid thermal response. Further the pivot bearing or support arrangements used in the gimbal ring assembly were not able to carry the required loads or withstand long term operations in vacuum at high temperatures. These factors and others indicated a need for a review of bimetal actuators to select more appropriate configurations. A summary of this configuration evaluation is presented in the following paragraphs, for: 1) cantilever strips, 2) gimbal-less mount, 3) spiral coils, 4) hairpins, 5) discs, 6) helical coils, and 7) flexure bearings.

Cantilever Concept

This concept shown in Figure 3.2-1 is of the type previously built and tested. The listing of advantages and disadvantages that follow are based on the experience with these previous test models. Additional calculations and supplementary laboratory tests under the current program have not altered this listing.

Advantages

1. Relatively simple
2. High gain
3. Easily fabricated
4. Easily assembled

Disadvantages

1. Poor thermal response
2. Poor mechanical strength
3. Difficult to locate forward bimetal support due to hot cavity
4. Sensitive to overtemperature
5. Subject to hysteresis
6. Poor mechanical advantage in support actuator arrangements
7. Introduces large bearing loads
8. Suitable forward bearings not available

Gimbal-Less Mount Concept

The concept shown in Figure 3.2-2 is an extension of the cantilever configuration. It introduces some simplification by eliminating the need for gimbal rings and fixing the concentrator rigidly to the generator. Analysis shows this type mount would work only with very thin bimetals and would be very inefficient both thermally and mechanically.

CANTILEVER CONCEPT

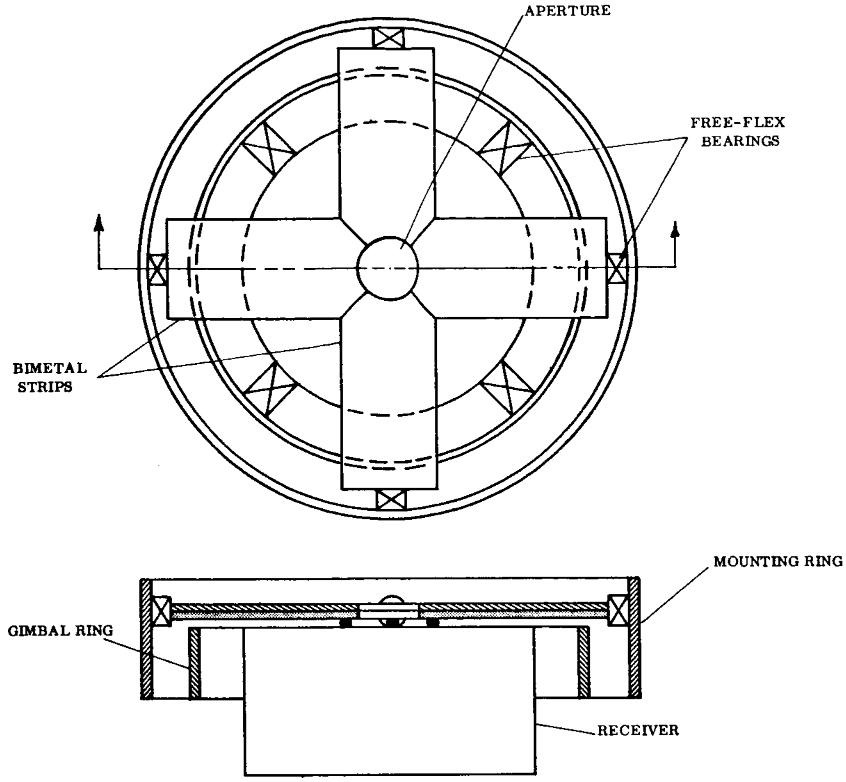


FIGURE 3.2-1

GIMBAL-LESS MOUNT

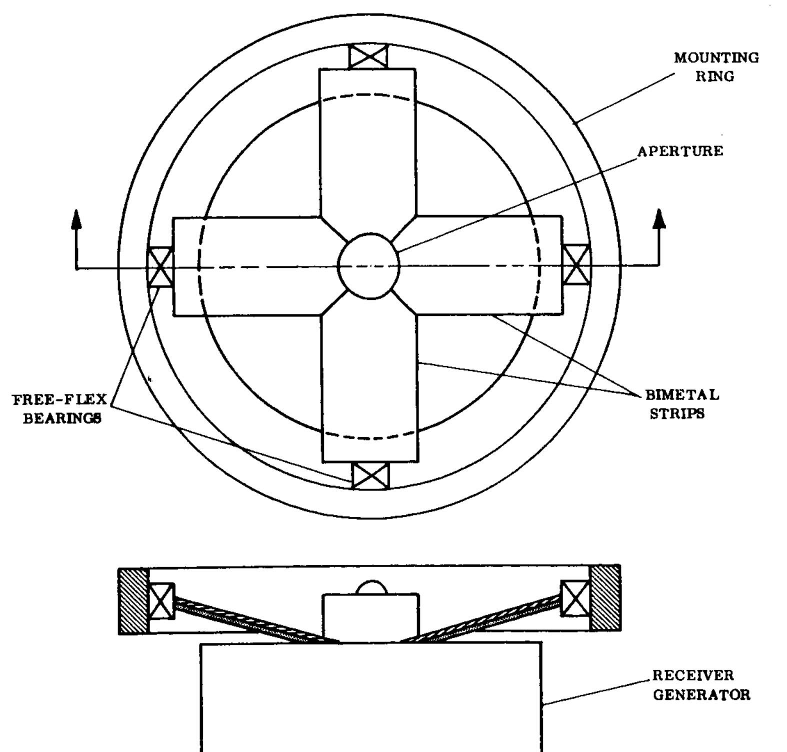


FIGURE 3.2-2

Advantages	Disadvantages
1. Few parts	1. Requires thin weak elements
2. Easy to fabricate and assemble	2. Elements must carry the weight of concentrator-generator
	3. Method of attachment of element tips very poor both thermally and mechanically
	4. Generator moves in and out of focal plane
	5. Low spring rate will reduce response characteristics

Spiral Coil Concept

Figure 3.2-3 shows the spiral concept which permits a large volume of bimetal material to be packaged in a small volume. This dense packaging means a considerable amount of work is made available for a given temperature change. Unfortunately this dense packaging also complicates heat transfer and heat rejection and greatly increases the thermal response time. This arrangement also suffers the need for a separate probe assembly, and special support or bearing structures, and presents an envelope which is not easily integrated in a thermionic generator.

Advantages	Disadvantages
1. High density packaging of actuator materials	1. Difficult to heat and cool
	2. Requires probe assembly
2. Moderate ease of fabrication	3. Requires complicated support or bearing structures
	4. Not easily integrated in generator structures
	5. Poor thermal response
	6. Possible low mechanical stiffness

Hairpin Configurations

One of the arrangements which shows considerable promise involves the use of hairpin or folded bimetal elements. This arrangement shown in Figure 3.2-4 offers the promise of double the deflection achieved with the cantilever type and eliminates the need for a forward support or bearing point. The open assembly also provides good heat transfer but the larger mass of the elements is found to result in a longer response time.

SPIRAL CONCEPT

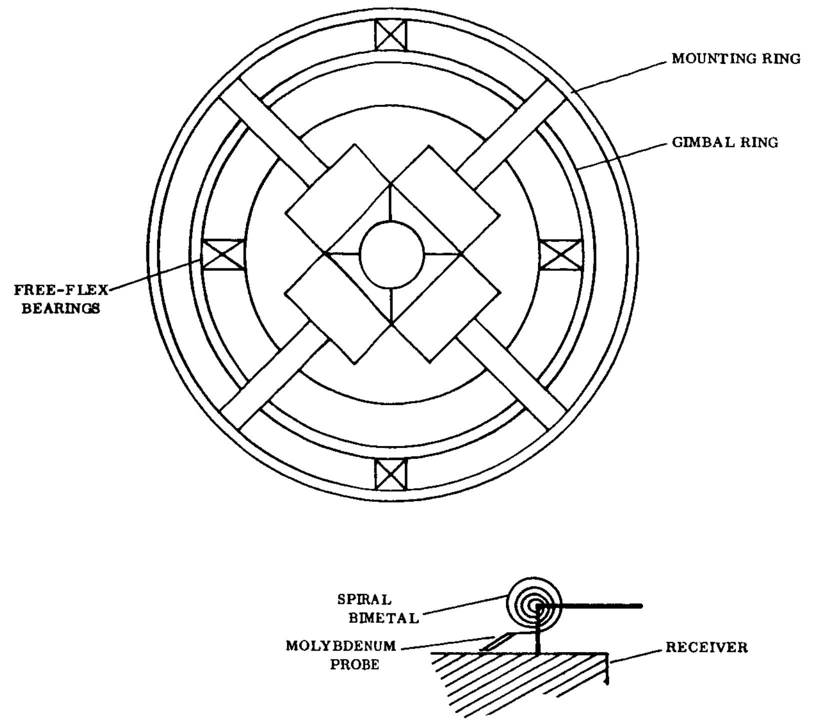


FIGURE 3.2-3

HAIRPIN CONFIGURATION

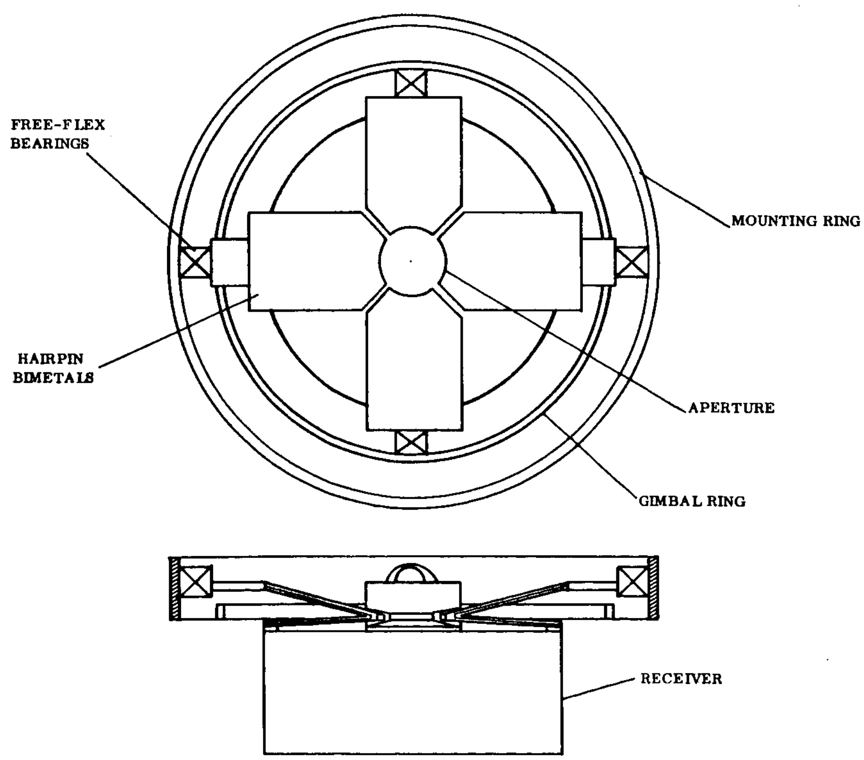


FIGURE 3.2-4

Also in order to fully utilize the deflection capabilities and to reduce or eliminate torsional effects at the point the elements are fixed to the generator a compound type bimetal must be used. This compound type assembly involves the interchange of high and low expansion materials on the same side of the bimetal element to provide control over the deflection mode at critical points. This assembly is of course much more difficult to fashion properly.

Advantages	Disadvantages
1. Large deflection capability	1. Longer thermal response time
2. Good heat transfer	2. Elements move relative to the focal plane
3. No forward support point required	3. Sensitive to overtemperature
4. Simple to fabricate and assemble	4. Must carry the weight of concentrator and generator
5. Moderate gain	5. Has 1/2 the stiffness of cantilever type for same element cross section
6. No hysteresis expected	

Disc Configurations

The disc actuator concept is similar in many respects to spiral type and would require similar mounting and sensor probe arrangements. Also because of the ability to package compactly there is a potential for large work outputs. The disc assemblies, as shown in Figure 3.2-5, suffer the same problems of thermal response and heat transfer and are mechanically very weak. It appears that in order to achieve the large deflections required it is necessary to use very thin disc elements. This aggravates heat transfer and makes the system quite soft with an attendant poor response characteristic. Also the disc assemblies and the incorporation of a suitable probe is quite difficult.

Advantages	Disadvantages
1. Large deflections	1. Poor thermal transfer
2. Elements removed from high temperature area	2. Difficult to fabricate
3. Large work output possible	3. Not easily integrated in generator
	4. Mechanically soft
	5. Poor response characteristics

DISC ACTUATOR

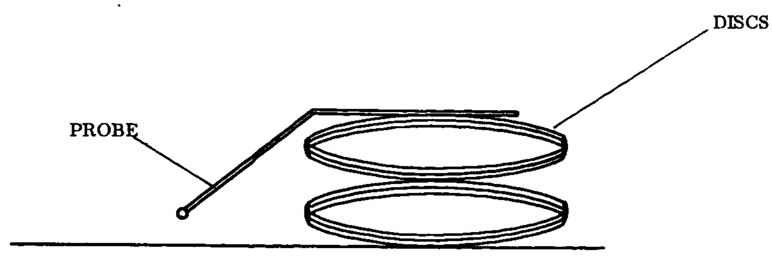
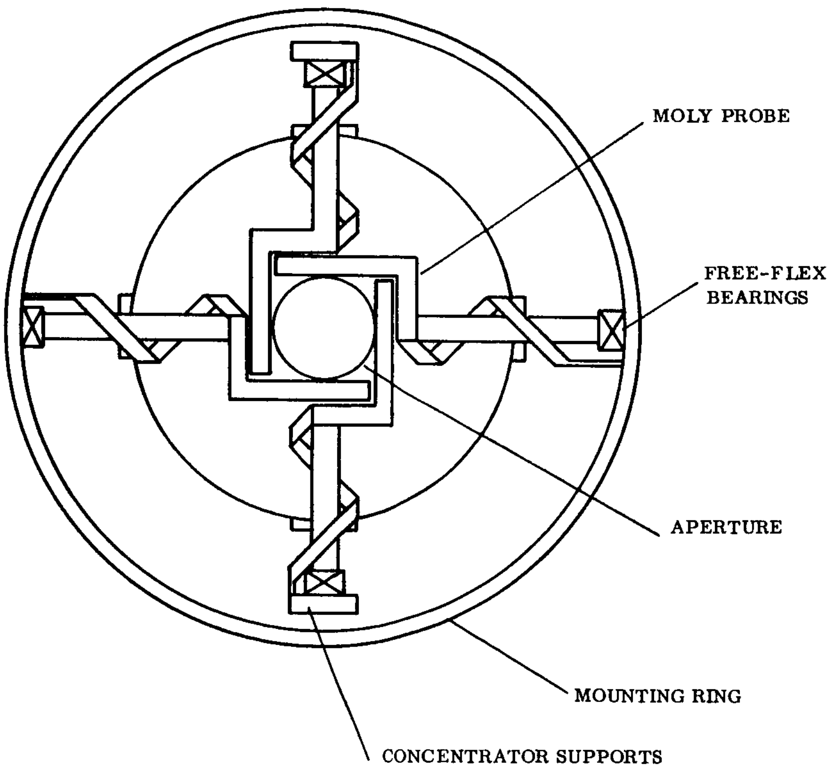


FIGURE 3. 2-5

HELIX CONFIGURATION



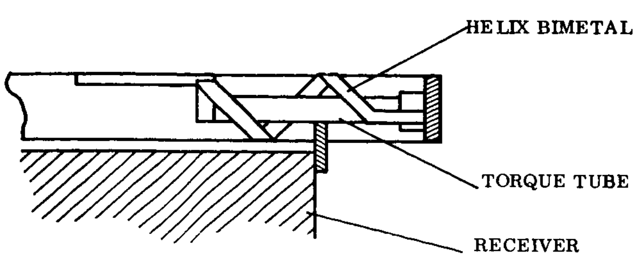


FIGURE 3. 2-6

Helical Coils

The most satisfactory combination of structural and physical properties is found in the helical type assembly shown in Figure 3.2-6. The actuating element is protected from overtemperature by the use of an efficient probe. Heat transfer into and away from the actuator element is straight forward. The element rotation is applied directly about the bearing axis and the amount of actual element deflection required is held to a minimum. The flexure bearings support all the load of the concentrator and generator and yield only to the torque induced by the elements. The assembly of the mount is also simplified by not requiring the elements to be preloaded under the ambient assembly conditions. Also the assembly is of such a shape as readily permit its installation in a thermionic generator. The only deficiencies lay in the area of thermal response and mechanical stiffness or spring rate.

Advantages	Disadvantages
1. Relatively simple construction	1. Poor thermal response
2. High gain	2. Mechanically soft
3. Induces rotation directly	3. Difficult to incorporate large volumes of bimetal material
4. Protected from over-temperature	
5. Good thermal transfer	
6. Easily integrated	
7. Bearings carry all load	
8. No displacement of sensors relative to focal plane	
9. Requires no preloading in assembly	

Flexure Bearing Configuration

This configuration (in Figure 3.2-7) is an attempt to combine the functions of both the frictionless flexure bearing and the bimetal actuator element. The flexible strips used in the bearings are replaced by bimetal elements and the inner sleeve caused to rotate with respect to the outer sleeve by heating or cooling the assembly. When applied in opposing pairs the bearing assemblies could be used to correct for concentrator mis-orientation. This concept was originally considered for use in mounts powered by either secondary optical systems or auxiliary electrically operated heaters. With the power input derived from sources other than the primary concentrator flux cone such a mechanism may have a potential advantage. In the present study which considers only the concentrator flux as a power source this concept is at a great disadvantage. The assembly cannot be miniaturized sufficiently to permit a close approach to the focal point and probes are not efficient in transferring energy rapidly over the longer path.

FLEXURE BEARING CONFIGURATION

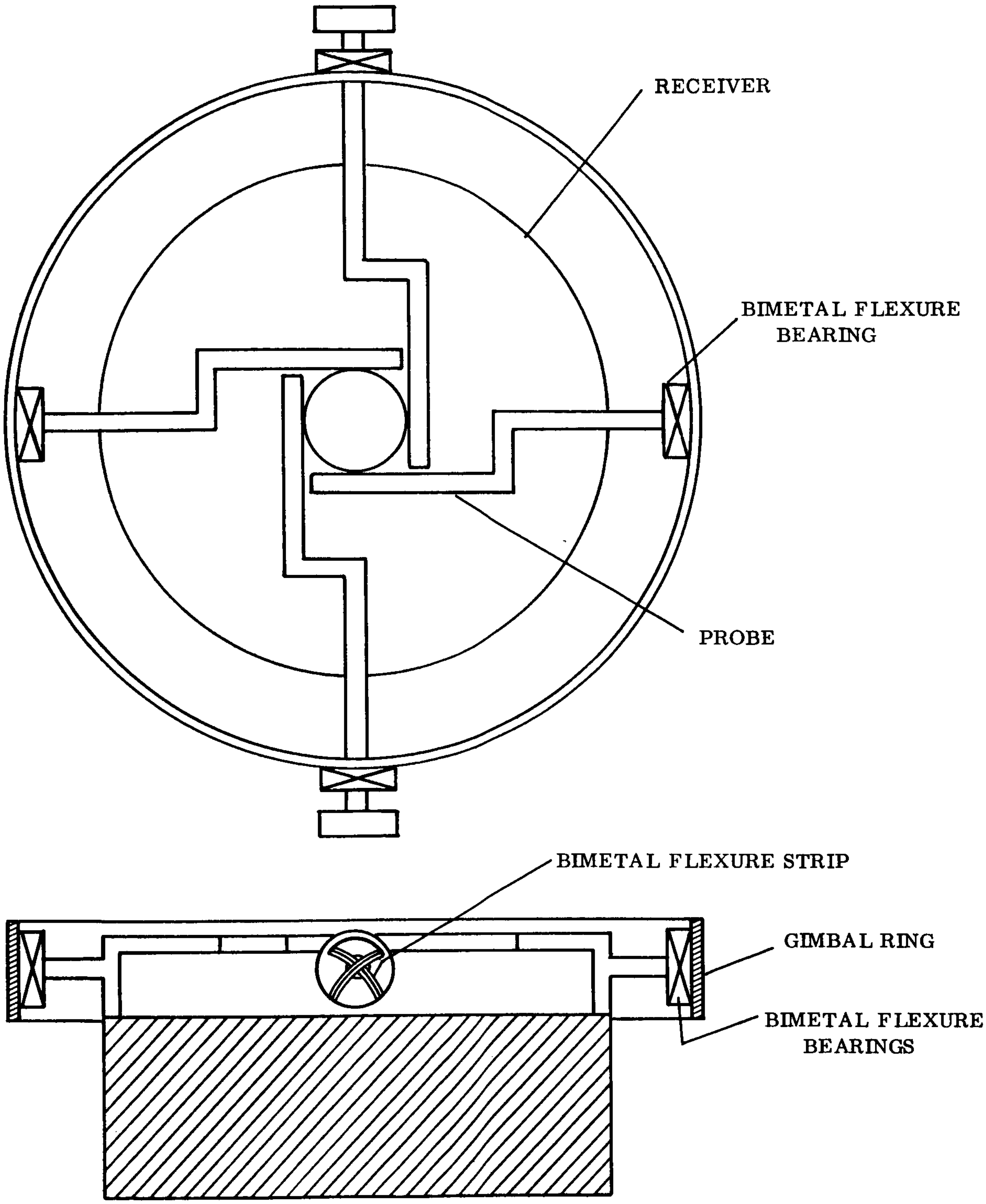


FIGURE 3.2-7

Advantages

1. Large load capacity
2. High gain
3. Removes elements from hot environment
4. Produces rotation directly
5. Requires no preloading

Disadvantages

1. Poor heat transfer along probe
2. Difficult to fabricate
3. Assembly must be relatively large
4. Poor thermal response

3.3 Review of Vapor Pressure Type Mechanisms

Vapor pressure actuated mounts have been tested only in component stages by TRW. The results of these limited tests and some preliminary analysis of potential mount designs have proven very favorable. Under this program the investigation of the various vapor pressure concepts has been persued in more detail along with the previously discussed bimetal concepts. In mount configurations designed to restore or control orientation by realigning the concentrator the requirement, design, and protective features of the sensor actuation mechanism is similar to that encountered with the bimetals.

It is necessary to insure against destructive overheating of the sensors, to insure good thermal and mechanical response characteristics, high gain, and general compatibility with the environment and power generating system. In addition the vapor pressure system must be protected against overpressure, charging fluid decomposition, and corrosion. Three basic actuation mechanisms have been considered in an effort to select the concept which will offer the best combination of features. These three are described as bellows type, bourdon tube type, and helix type. Many arrangements of each is possible but for the most part the overall characteristics are not appreciably changed by such arrangement changes.

Bellows Actuator Type

Bellows type assemblies are considered to be the easiest and most conventional approach to obtaining actuation. Current technology in the bellows fabrication area has made available a number of small bellows of stainless construction with burst pressures well over 1500 psi and with deflection and spring characteristics which are appropriate for use in a heliotropic mount. A number of arrangements are possible with the compact bellows assemblies most of which are quite suitable for integration with a thermionic generator assembly. Also by varying the bellows size a wide range of motive force or torque and motion can be made available to facilitate the adaptation of the mount to other systems.

The gain of a bellows system is also easily varied with most reasonable working fluids since the rate of change of vapor pressure with temperature increases with an increase in ambient temperature. A typical assembly is shown in Figure 3.3-1.

Advantages

1. Efficient force generation
2. Negligible hysteresis
3. High and easily varied gain
4. Compact and easily adapted
5. Long cycle life
6. Good thermal and mechanical response
7. Can incorporate internal damping for system stability

Disadvantages

1. Moderately expensive
2. Difficult to fill properly
3. Must be protected against gross over pressure
4. Produces rotation indirectly

Bourdon Tube Actuators

Assemblies of the type shown in Figure 3.3-2 were considered for mount application. The unit shown was previously tested by TRW and found to be relatively inefficient as an actuator mechanism. The assembly does not possess sufficient strength to carry the concentrator generator weight and the amount of torque generated is small compared to the bellows mechanisms. The device has the advantage of eliminating the need for any additional bearings but presents a rather formidable assembly problem and requires a somewhat large and inconvenient shaped assembly.

Advantages

1. Moderate gain
2. Eliminates the need for bearings
3. Good response characteristics
4. Produces direct rotation

Disadvantages

1. Complicated assembly with many joints
2. Large size
3. Inefficient
4. Low strength

Helical Tube Actuator

The use of a pressurized helical tube to produce motion results in a configuration very similar to that shown for the helical bimetal assembly in Figure 3.2-6. The probe is replaced by a sensor and connecting capillary. This assembly is somewhat more desirable than the bourdon tube configuration in that it is more compact and has the use of external support bearings. Also the assembly is simpler and perhaps easier

BELLOWS MOUNT CONCEPT

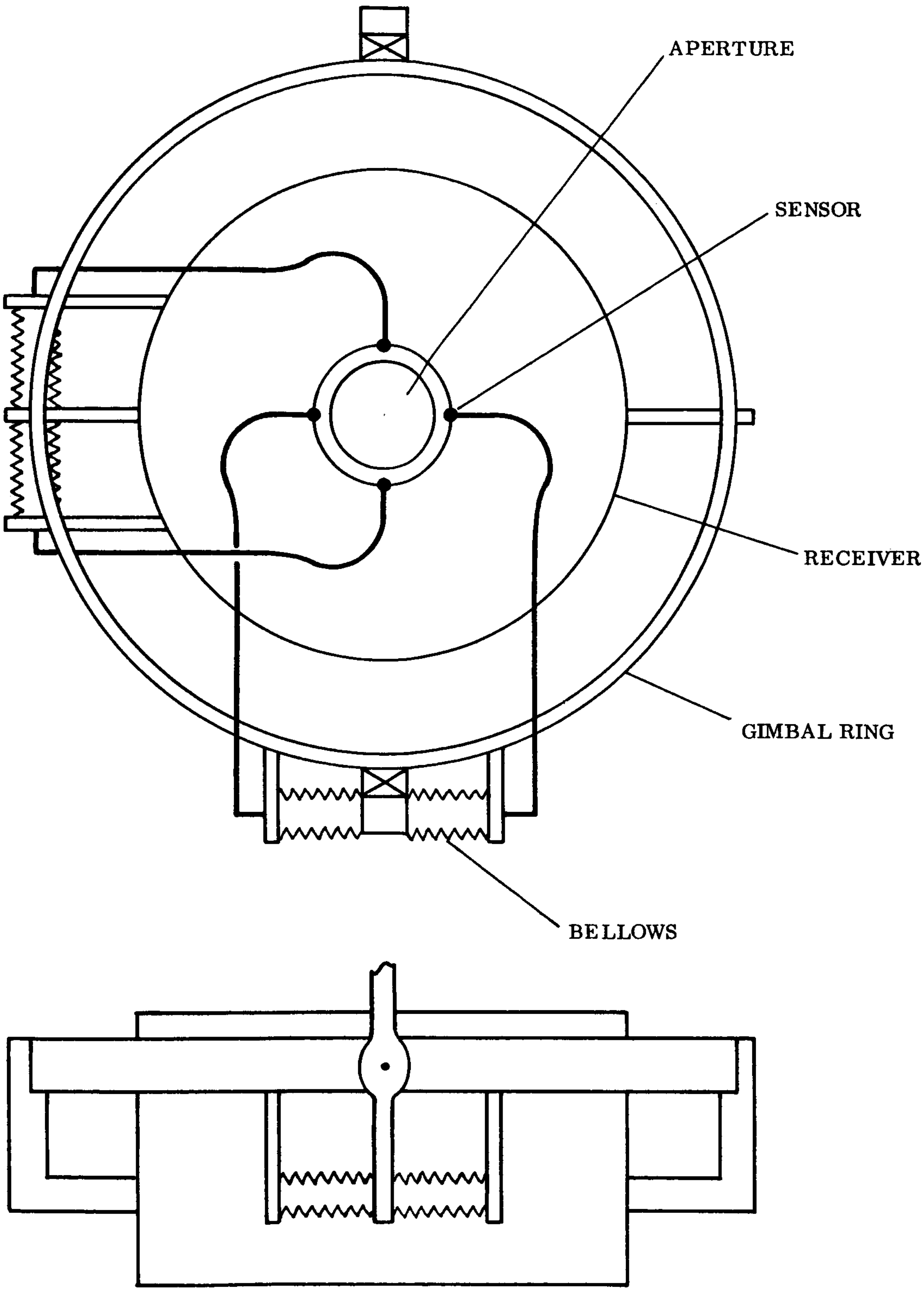
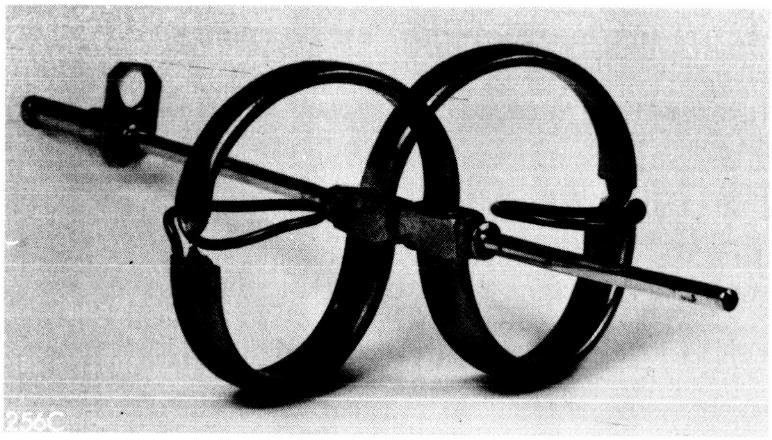
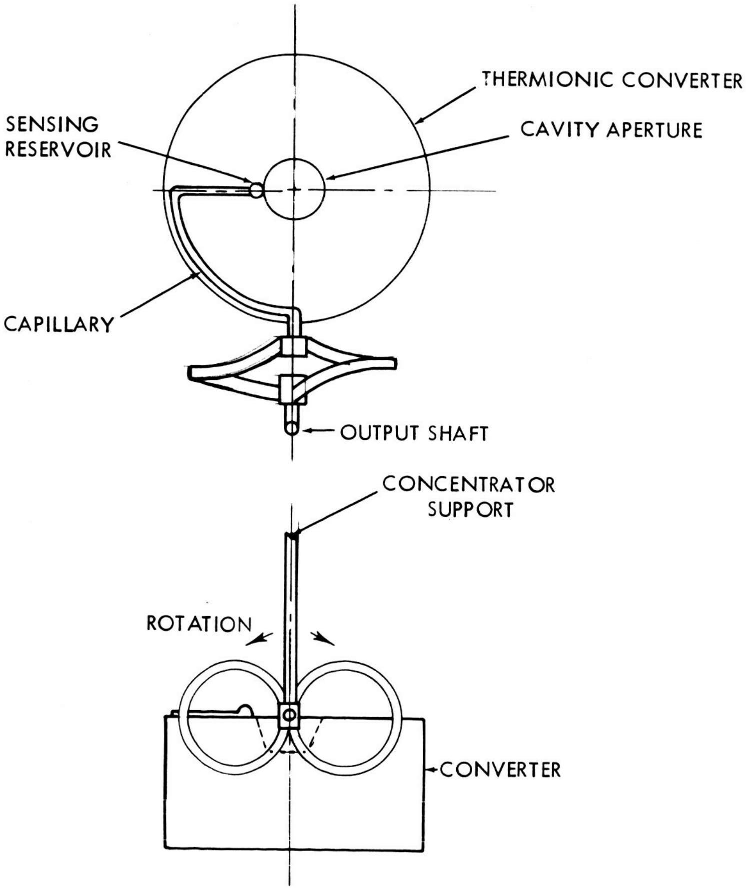


FIGURE 3.3-1



BOURDON TUBE ACTUATOR



BOURDON TUBE ACTUATOR MECHANISM

FIGURE 3.3-2

to integrate with a generator. Using a sensor probe provides for good thermal response and both this assembly and the bourdon tube assembly require smaller sensor charge inventories because of the way motion is produced in the flattened tube assemblies.

Advantages	Disadvantages
1. Good response characteristics	1. Low efficiency
2. Small sensor inventory	2. Design is not flexible or easily adaptable
3. Produces direct rotation	3. Assembly is difficult
	4. Mount is soft

3.4 Preliminary Design Studies and Analogue Computer Evaluation of Proposed Mount Concept

Based on the review of all bimetal and vapor pressure actuator concepts two mechanisms were selected for a more detailed evaluation. These were of the helical bimetal and the bellows type. The mount designs were developed around state of the art hardware. The designs assume a 60 inch diameter 60 degree rim angle concentrator weighing 10 pounds. This concentrator would represent a moment of inertia of approximately 17.5 lb in. sec.^{2} The generator is of the cesium vapor type operating at 2000°K, weighing approximately 5 pounds, and has a 100 watt output capacity.

A parametric study of the helix bimetallic configuration was carried out and found to show considerable promise in terms of the resulting element characteristics. In this configuration it appears easily possible to obtain a reasonably stiff system with a fairly high natural frequency and to get high gains and torques sufficient to move the concentrator.

A summary of these characteristics is shown in Figures 3.4-1, 3.4-2, and 3.4-2. Figure 3.4-1 shows the natural frequency of the concentrator mass-mount spring system. The use of a t/L ratio of 0.01 and a volume of 0.1 in^3 would give a practical bimetal element of 4 x 0.62 x 0.04 inches. The natural frequency would be 1.5 radians per second.

From Figure 3.4-2, it is seen that a 20°F temperature change would produce 1° of mount rotation. Figure 3.4-3 in turn indicates an unbalanced torque of 3.6 in. oz. would be induced by a 20°F temperature unbalance in opposing elements. This typical combination would be satisfactory in most instances although not necessarily optimum.

UNDAMPED NATURAL FREQUENCY VS. (t/L) RATIO

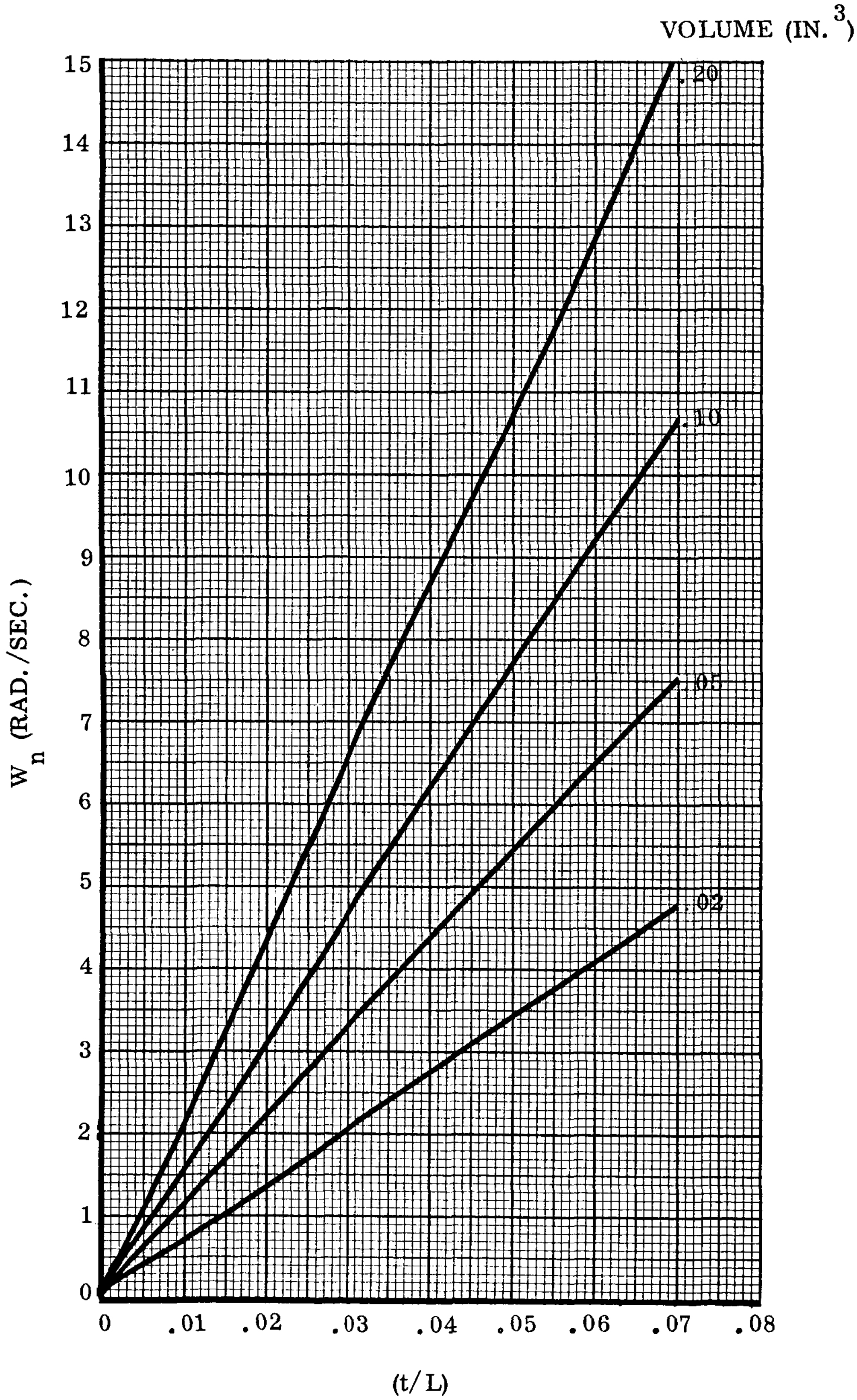


FIGURE 3.4-1

TEMPERATURE DIFFERENCE BETWEEN SENSORS
REQUIRED PER DEGREE ROTATION VS. (t/L) RATIO

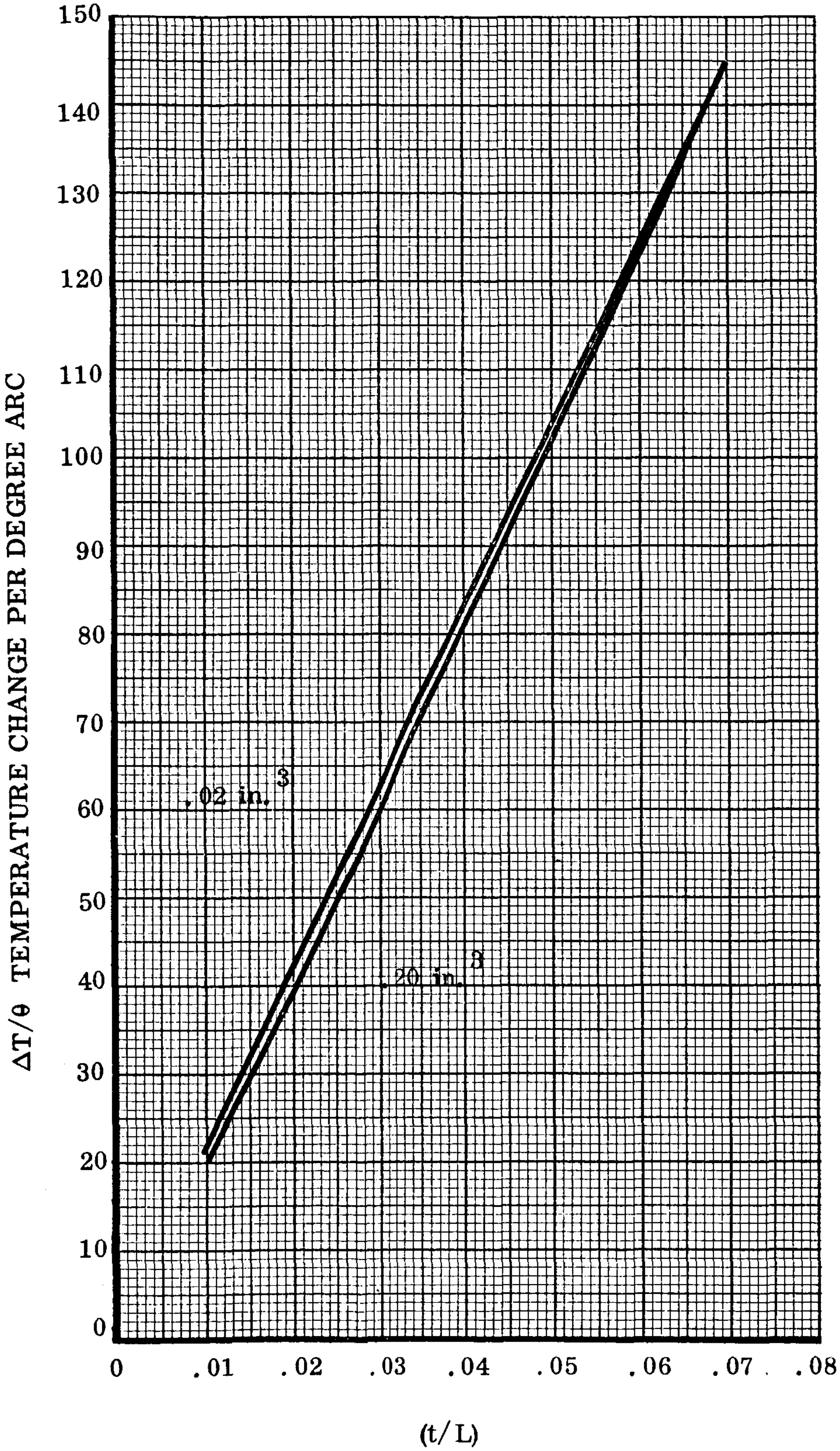


FIGURE 3.4-2

TORQUE PRODUCED PER DEGREE F TEMPERATURE DIFFERENCE BETWEEN SENSORS VS. (t/L) RATIO

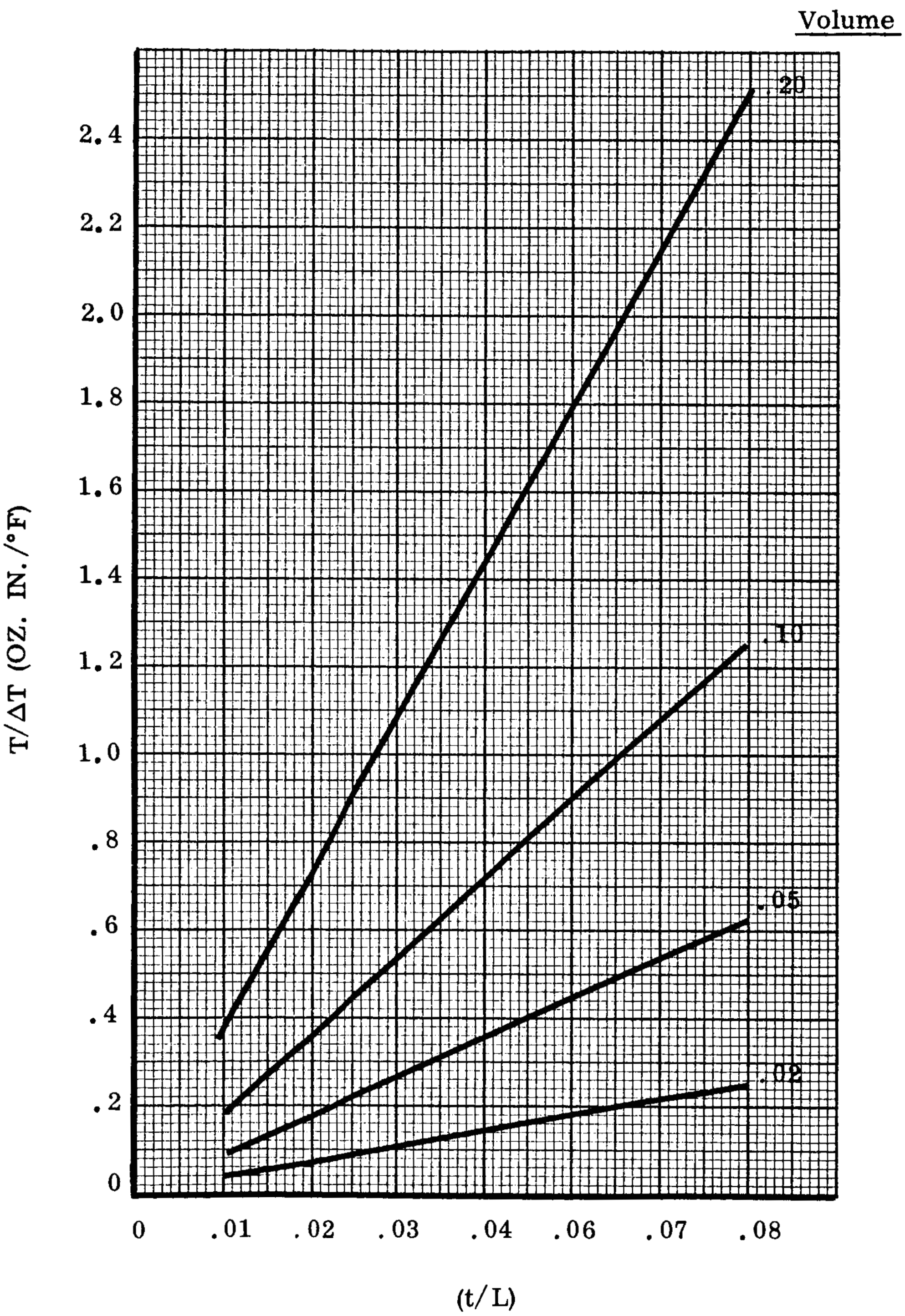


FIGURE 3.4-3

The inadequacy of the bimetallic concept as determined by analysis and laboratory test lies in its relatively poor thermal response. Tests simulating a helix configuration showed that the thermal time constant of such an assembly is on the order of 6 minutes or greater. This response is consistent with the thermal response achieved with the original leaf type heliotropic mount built by TRW and shown in Figure 1-2. It has been concluded therefore that the conflict between requirements for rapid thermal response and mechanical stiffness can not be completely reconciled.

The concept selected for development is therefore the bellows type. A review of the physical and mechanical requirements of an appropriate bellows-sensor-mount configuration was made. It was determined that no insurmoutable difficulties would be encountered. A survey of bellows manufacturers was made to select the most appropriate components and characteristics. Sensor sizes were calculated, thermal response times estimated and confirmed satisfactorily by actual laboratory tests of similar sensor configurations. A review of all reasonable charging fluids was made and mercury was selected on the basis of its pressure characteristics, stability at elevated temperatures, and availability in a very pure state.

Based on the various components available, a tentative mount design was developed. From this design and with the particular properties of each key component, an analog computer program was prepared. The complete mount-concentrator assembly was simulated in considerable detail with the only significant linearization being the reduction of the radiant transfer term for the sensor expressed as a direct function of sensor temperature. For a limited range, however, the error here is small.

The simulation results were both informative and very satisfactory in terms of confirming expected dynamic mount characteristics. Of great importance was the clear indication of a need for 10 to 20 times the calculated critical damping based on concentrator inertia and bellows spring rate alone. The system was evaluated on a parametric basis to determine the effect of minor changes in components on system characteristics. This parametric study indicated considerable latitude in several areas and pointed up several ways in which mount performance could be improved. The study also showed that the positioning of the sensor about the cavity aperture will be extremely important in establishing the proper ambient conditions as well as to avoid extremes in temperature or pressure in the sensor-bellows assembly. The general performance characteristics as determined by the computer study are summarized in Figures 3.4-4 and 3.4-5.

Figure 3.4-4 shows the dynamic gain and frequency response characteristics of the mount as determined for the initial design with the addition of a damping factor of 20 times the critical. The system is seen to be stable for frequencies up to at least 0.16 cps. It is of interest to note that a recent NASA space station specification for a 20 to 40 kw power system required a system compatible with a 0.4 radians per second spin. This corresponds to 0.06 cps which is well within the capability of this mount. This mount design is for a zero g environment however, and therefore would not be entirely suitable if the radial location produced large normal accelerations and moments about the mount bearings. The parametric studies are summarized, in part, in Figure 3.4-5 where concentrator alignment error is plotted against the vehicle disturbine frequency assuming a 5 degree vehicle attitude error.

BELLOWS ACTUATOR MOUNT GAIN AND
FREQUENCY RESPONSE CHARACTERISTICS

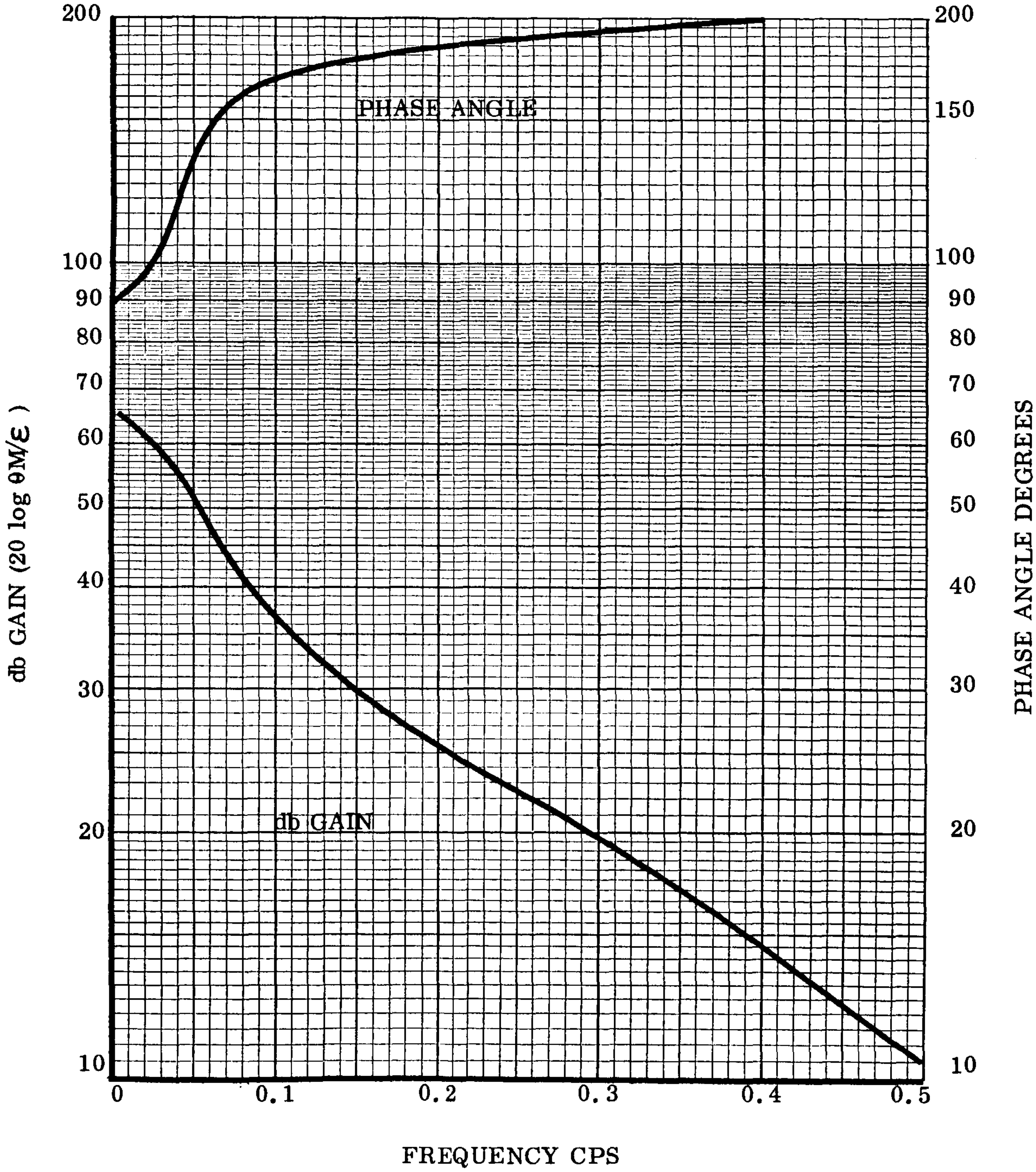


FIGURE 3.4-4

HELIOTROPIC BELLOWS ACTUATOR PARAMETRIC STUDY

ALIGNMENT ERROR VERSUS DISTURBING FREQUENCY WITH $\theta_v = \pm 5°$

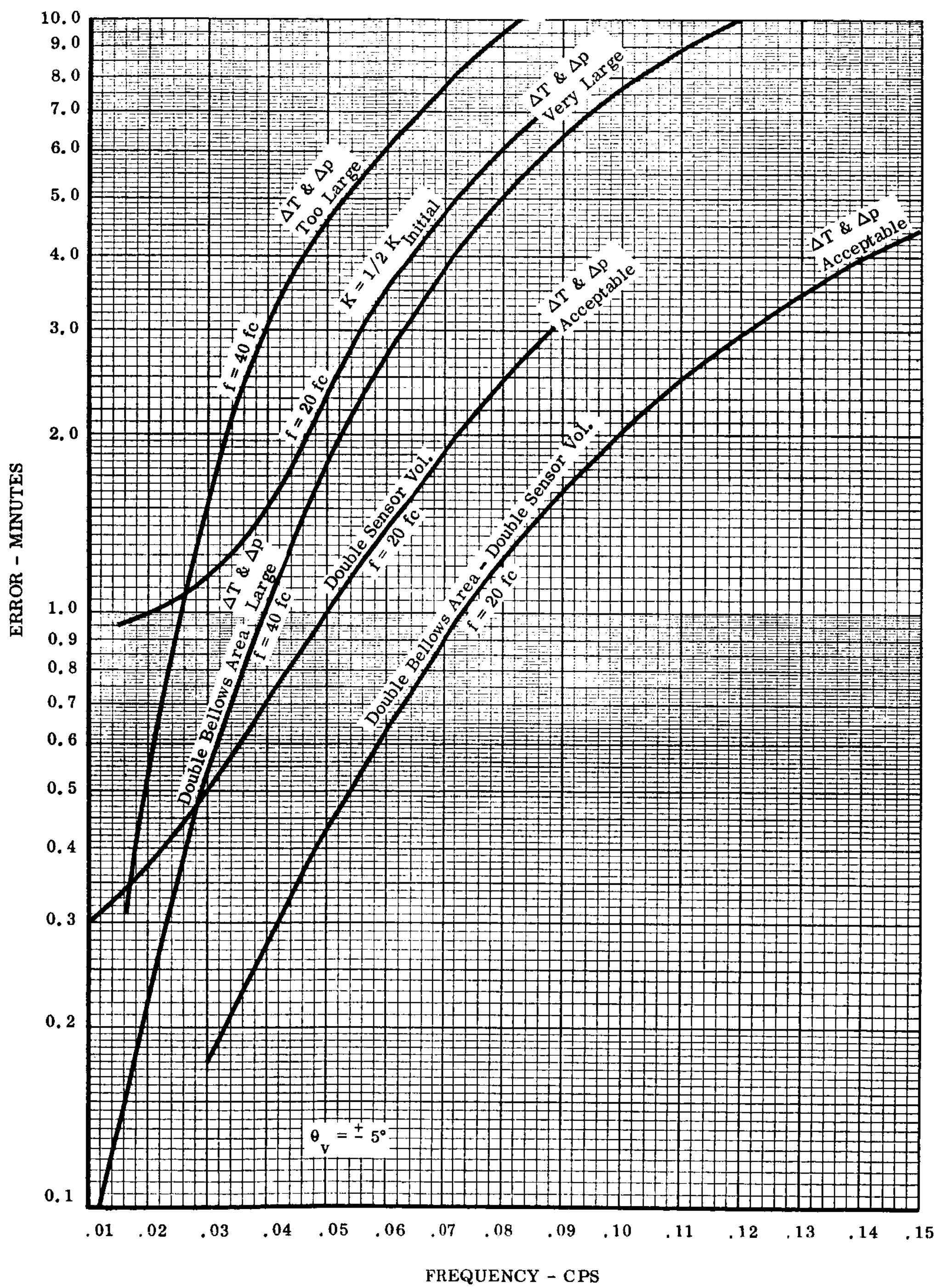


FIGURE 3.4-5

4.0 MOUNT DESIGN

4.1 Mount Test Configuration

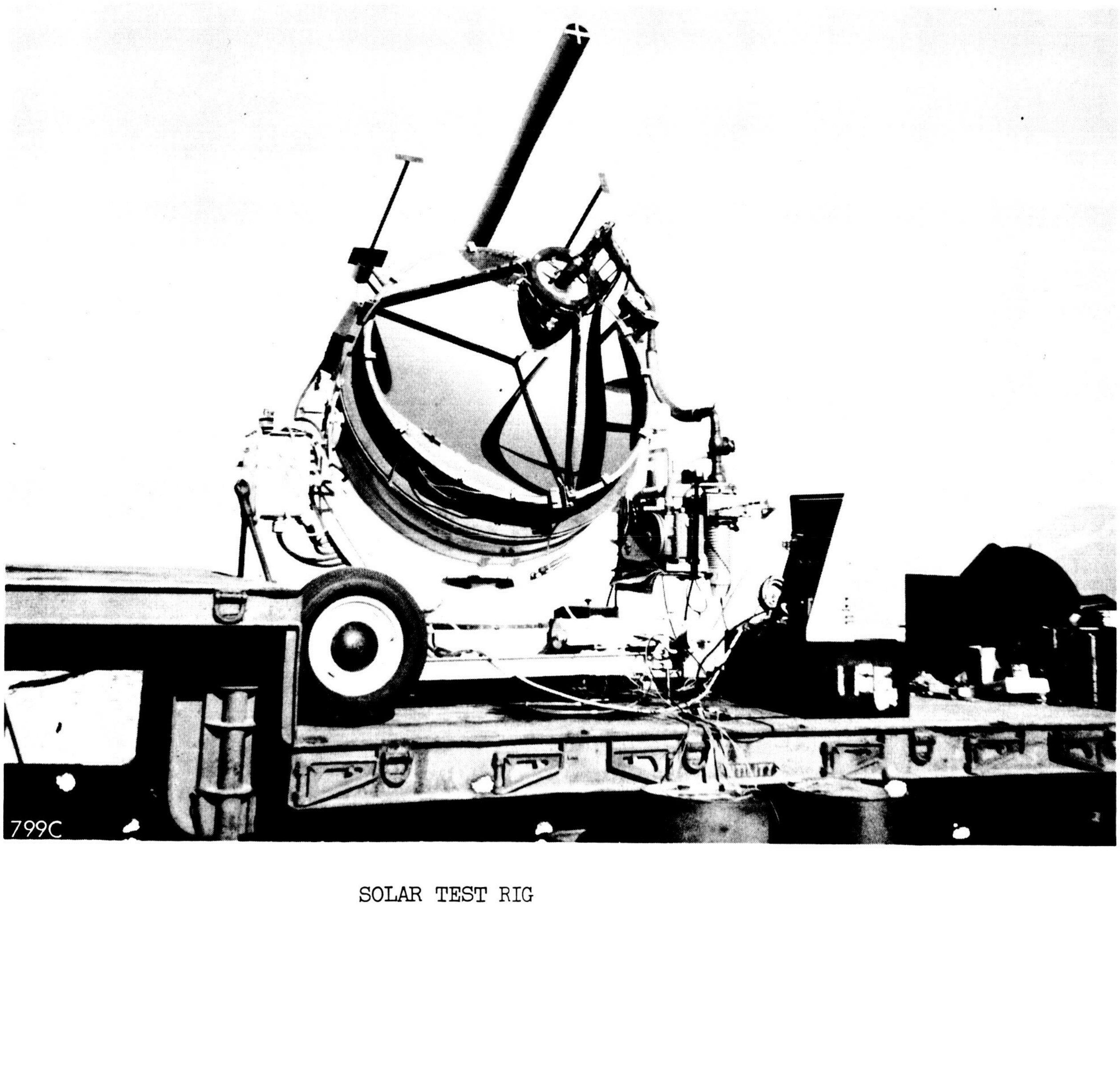
Many factors must be considered in the design of a heliotropic mount which will be suitable for a thorough performance evaluation. The mount must be a prototype in the sense that it meets all the requirements in terms of size, response, strength, environment, and practical space and volume limitations. Also the prototype mount must be capable of being tested in a meaningful way to determine its space system capabilities while under the constraints of earth bound test conditions. Finally it is very desirable that as much adjustment as possible be built into the mount to permit changes to be made during the testing without incurring the need for extensive redesign or modification.

The prototype mout as previously stated is designed to operate with a 5 foot diameter 60 degree rim angle concentrator and a 100 watt thermionic generator. The physical properties of these principle components were used to verify favorable mount performance in the computer study. The detailed characteristics attributed to these principle components were derived from actual test results obtained with the TRW solar tracker, and experience with several thermionic generators designed for a nominal 100 watt output. The TRW solar tracker with its vacuum environmental chamber and pumping system is shown in Figure 4.1-1.

Extensive flux profile measurements have been made for the concentrator in the TRW tracker rig. These profiles for some tests include the optical dispersion and attenuation effects of the polished bell jar dome which encloses the environmental chamber. Other measurements of power available for a range of solar constant have also been made and used to determine concentrator reflectivity, bell jar transmission, cavity absorber efficiency (for thermionic generators), and the effects of small orientation errors or displacements from the focal plane. The values derived from these tests and used as the design criteria in this program are listed as follows:

1. Concentrator effective area - 18 ft^2
2. Concentrator reflectivity - 80%
3. Bell jar transmission - 82%
4. Cavity absorptivity (approximate) - 85 to 90%
5. Optimum cavity diameter - 9/16 inch for 2000°K operation - zero misorientation
6. Cavity radiation loss (2000°K) - 82 $watts/cm^2$

Figure 4.1-2 shows a plot of the flux profile as measured in three planes with a Ruge radiometer. The fringe regions of these flux profile curves were subsequently averaged and used to generate a curve of sensor input power as a function of radial distance from the concentrator axis. This plot of sensor power input is shown in Figure 4.1-3 and



SOLAR TEST RIG

FIGURE 4.1-1

FLUX PROFILE DATA FOR FIVE FOOT DIAMETER SOLAR CONCENTRATOR
(DATA WITH PYREX DOME)

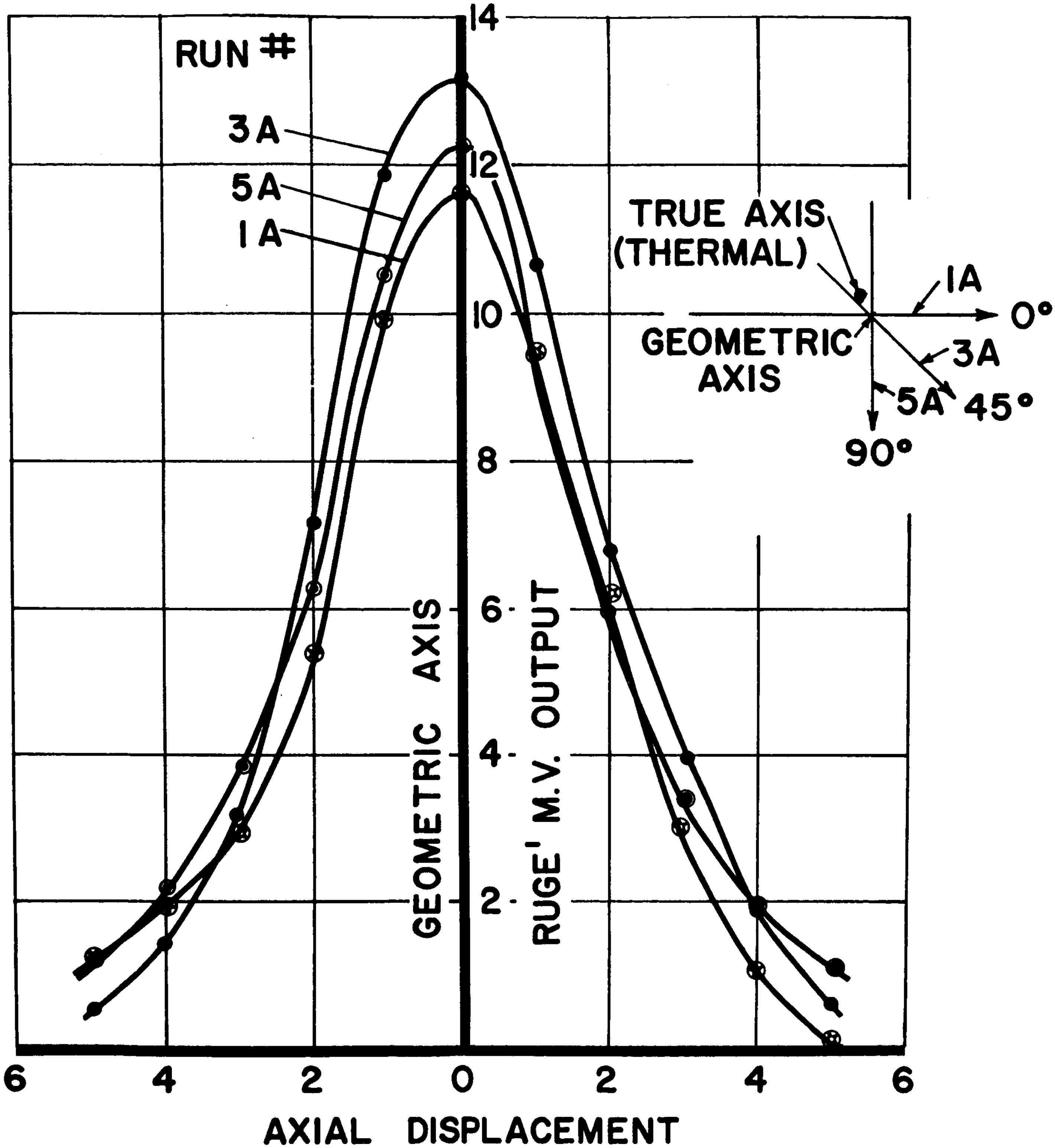


FIGURE 4.1-2

SENSOR INPUT POWER VERSUS LOCATION

(1 BTU/SEC = 1.054 KW)

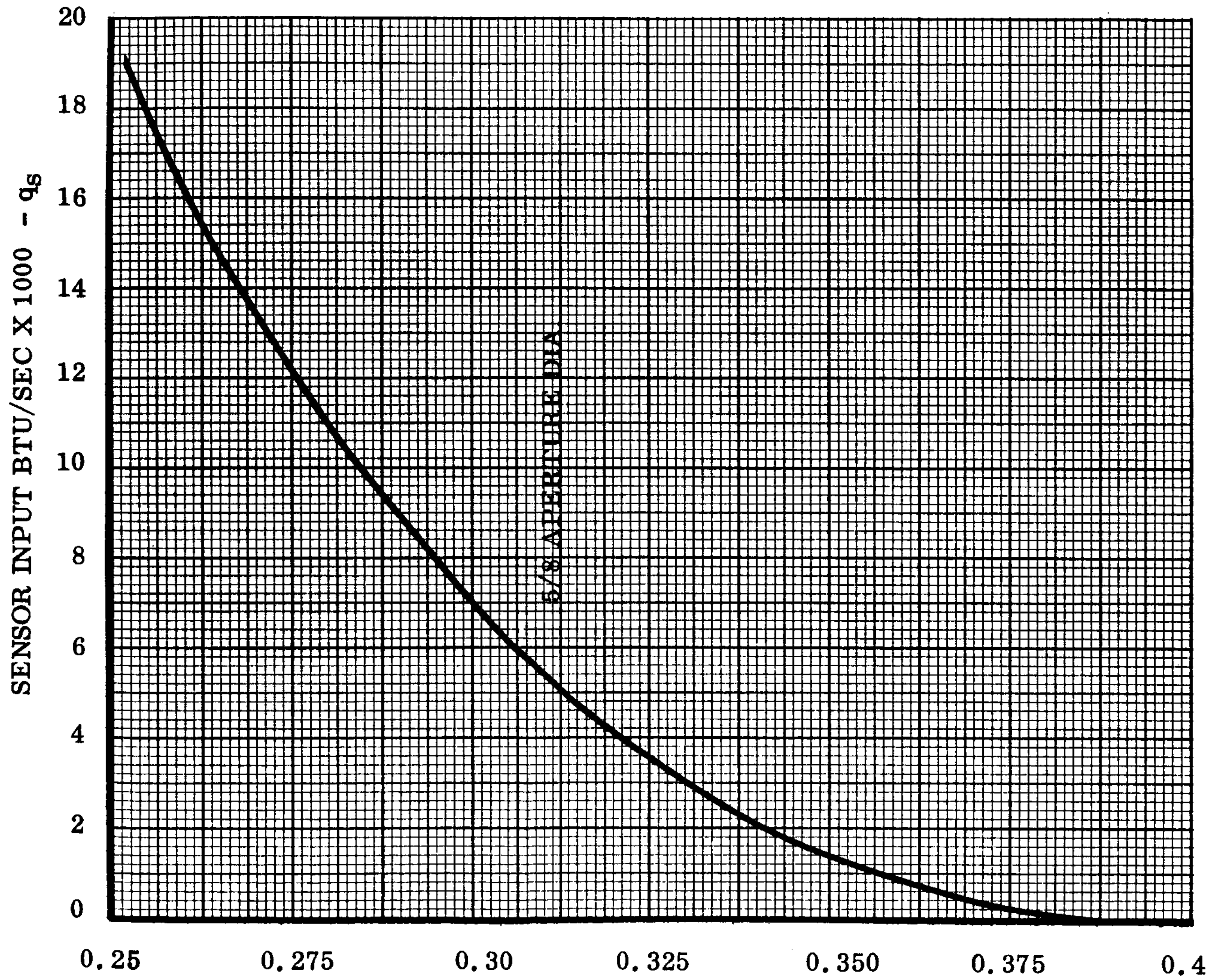


FIGURE 4.1-3

served in the computer study using a nominal sensor design point location of 5/16 inch from the concentrator axis.

The generator configuration shown in Figure 4.1-4 is for the most recent TRW design executed under contract to the Air Force. It was felt that such a generator is a typical 100 watt unit and therefore was used in defining the working environment and integration requirements for the prototype heliotropic mount. This basic generator design was converted into a calorimeter assembly with several modifications of the body portion made to facilitate mounting of heliotropic hardware.

The calorimeter is of the power distribution type previously built and operated on past TRW solar thermionic test programs. It simulates in all respects the temperatures, temperature distributions, approximate geometry, and materials used in an actual generator assembly. Also as a calorimeter device it is able to measure input solar power and power distribution in the event the concentrator is misaligned and the flux transfer is no longer uniform. Such a calorimeter permits a good evaluation of power available for direct conversion by a thermionic device, can be fabricated at a fraction the cost of equivalent generator, and serves admirably in the evaluation of the heliotropic mount in terms of providing a realistic environment and assisting in the evaluation of mount performance under solar test. The design points chosen or calculated for the calorimeter are listed as follows:

1.	Cavity temperature	1700°C
2.	Cavity design power input (assume a solar constant of 75 watts/ft^2 at the TRW Cleveland test site)	797 watts
3.	Calorimeter body temperature	442°C
4.	Calorimeter element radiator temperature	490°C
5.	Cavity aperture diameter	5/8 inch
6.	Cavity absorptivity	.90
7.	Cavity radiation loss	161 watts
8.	Calorimeter elements heat flux (each)	151 watts
9.	Stray power losses	32 watts
10.	Radiator element emissivity	.85
11.	Effective radiator area (each)	94 cm^2

ADVANCED SOLAR THERMIONIC GENERATOR UTILIZING SERIES 310 CONVERTERS

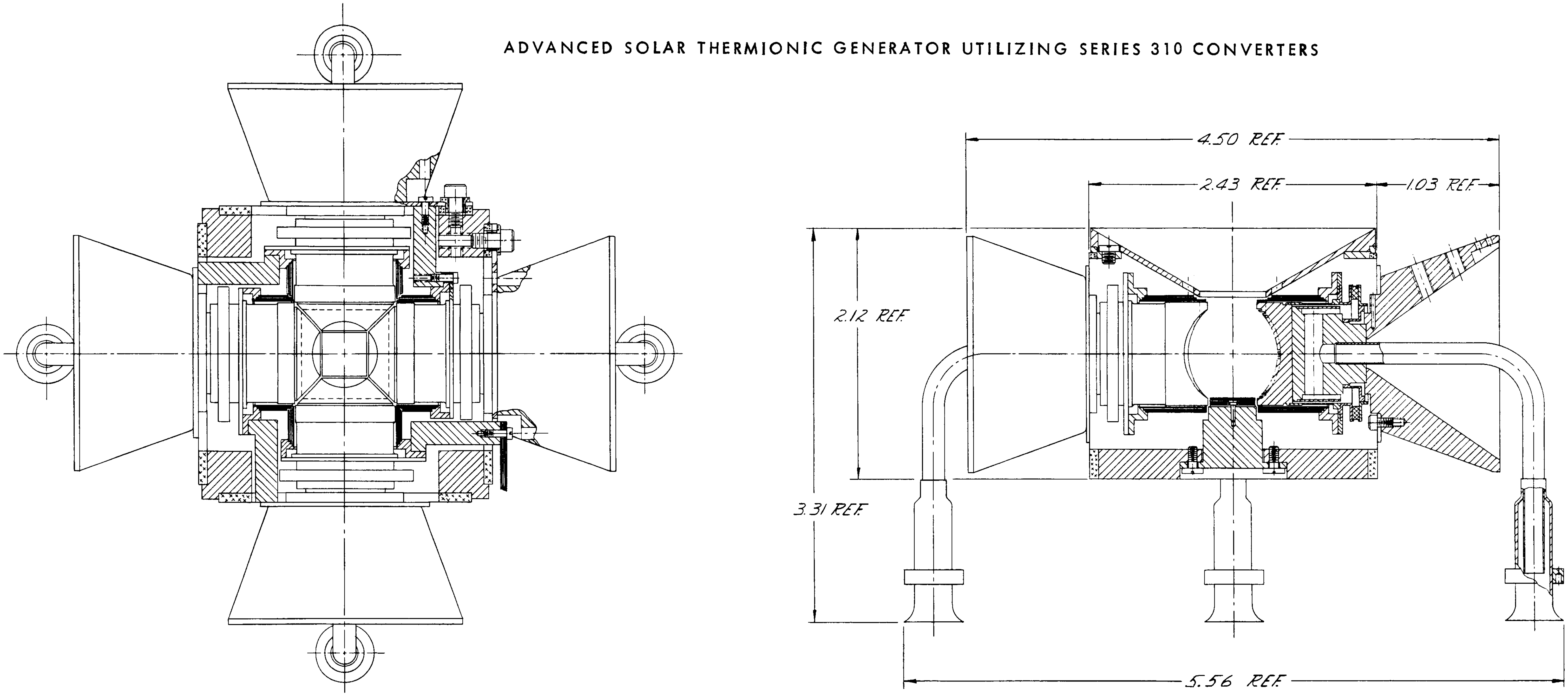


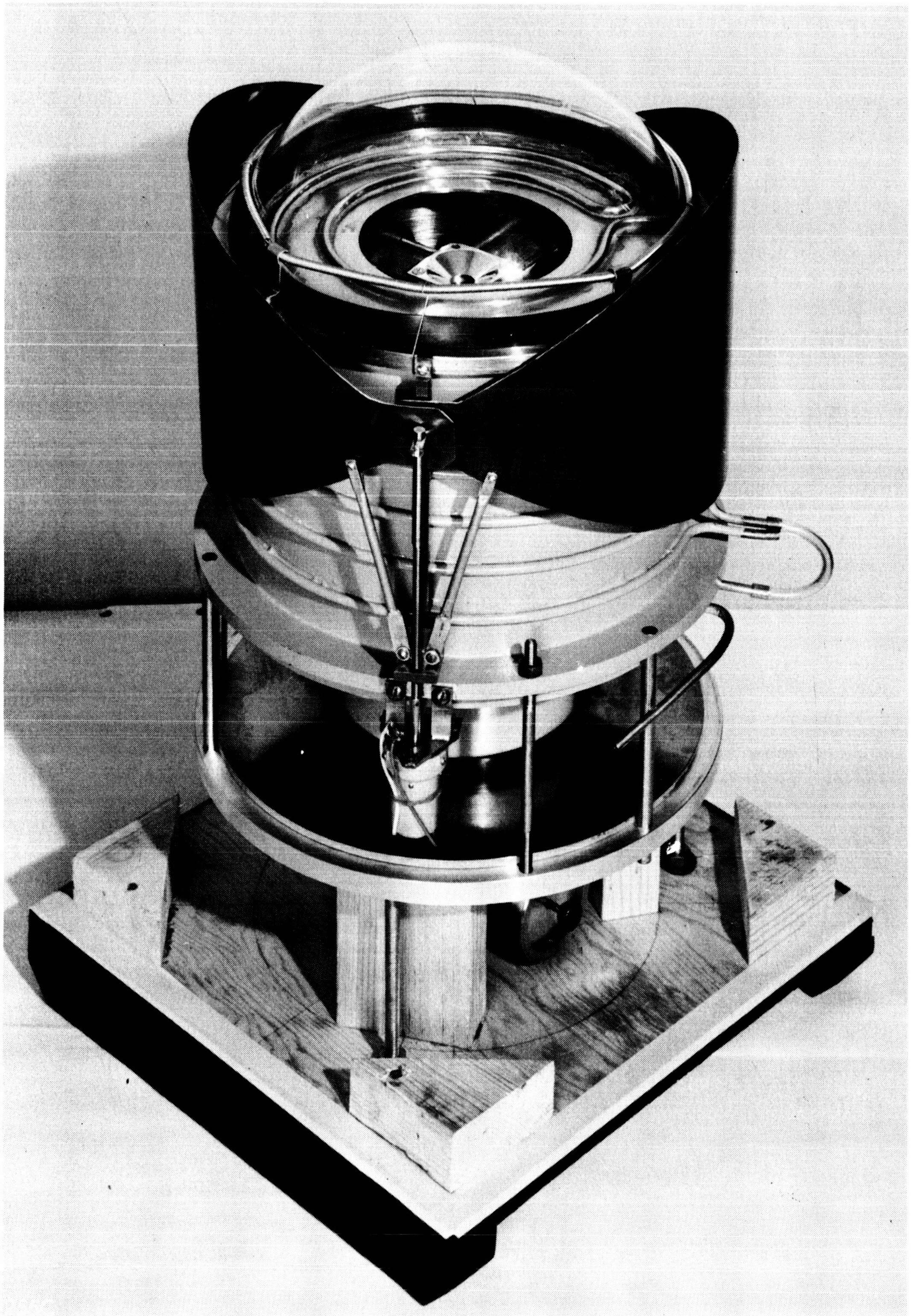
FIGURE 4.1-4

The power distribution calorimeter operates by measuring the ΔT between two points located on the conductive shaft between the hot cavity and the radiator. By knowing the distance between these points and the area and cpnductivity of the shaft, the equivalent power transfer can be determined. The actual assembly is also calibrated by electron bombardment techniques which permits an accurate measure of element input power as a function of the measured ΔT. Side losses and support losses are held to minimum by design and efficient multilayer shielding as in the thermionic generator. Small errors which show up during calibration may be corrected to insure nearly identical performance in each calorimeter element.

The body modification to the calorimeter consisted of altering the generator design shown in Figure 4.1-4 to include four flats between the element radiator assembly to facilitate mounting the heliotropic hardware. Also approximately 1/4 inch of space is now available above the calorimeter elements to permit the location of the sensor probes at the edge of the cavity formed by the head pieces of each element. The calorimeter and the mount hardware including the support members and base plate assemblies are designed to be compatible with TRW's existing environmental test chamber. The base plate is designed to mate with the solar test chamber shown in Figure 4.1-5 and with other glass bell jars on TRW laboratory test stands. This plate also includes the receptacle for all power and instrument leads, and special leveling or jack assemblies to permit minor adjustments of the calorimeter relative to the focal plane and axis while solar testing under vacuum.

4.2 Mount Assembly

The preliminary design evaluated on the analogue computer was developed by mating the most favorable stock stainless steel bellows available with the calorimeter assembly. The bellows was chosen based on its burst pressure, spring rate, diameter and length, and stroke. A review of 6 potential bellows lead to the selection of a Flexonics Inc. bellows having 25 convolutions, an effective area of .06 sq. in. a maximum pressure of 1500 psi and a total deflection of approximately .125 inches. The sensor ambient temperature was calculated based on the heat balance attained within the confines of the generator while subject to the solar flux input, radiant transfer from the hot cavity, and reasonable conduction and radiation losses from the sensor body. This temperature was established at 1059°F and was found to correspond to a mercury vapor pressure of 281 psi. Using this pressure, the effective area of the bellows, and selecting a working radius of .8 inches the actuator design torque, sensor inventory and thermal mass were determined. As previously discussed these values were used in the simulation and varied over a small range to obtain parametric type data to determine methods of readily improving the mount characteristics. The computer study indicated a larger bellows area, larger sensor thermal mass, and a softer spring rate would offer even better performance. The computer also indicated a need for an increase in the viscous damping factor of from 10 to 20 times the value calculated based on the concentrator mass and selected bellows spring rate alone. Taking all these factors into account the finalized design was executed.



ENVIRONMENTAL TEST CHAMBER

FIGURE 4.1-5

A complete layout of the calorimeter and mount assemblies is shown in Figure 4.2-1. The basic calorimeter can be seen to simulate very closely the general shape of the thermionic generator which served as the model. The mount actuator assemblies are shown as four identical attachments which are simply screwed into place on the flats between each radiator assembly. This latter arrangement permits the substitution of mount assemblies at will and would be a very desirable feature in any system which was undergoing qualification tests prior to incorporation into a space vehicle. It also permits the generator and mount hardware to be fabricated separately, tested separately, and integrated only at the point where system assembly or qualification was required.

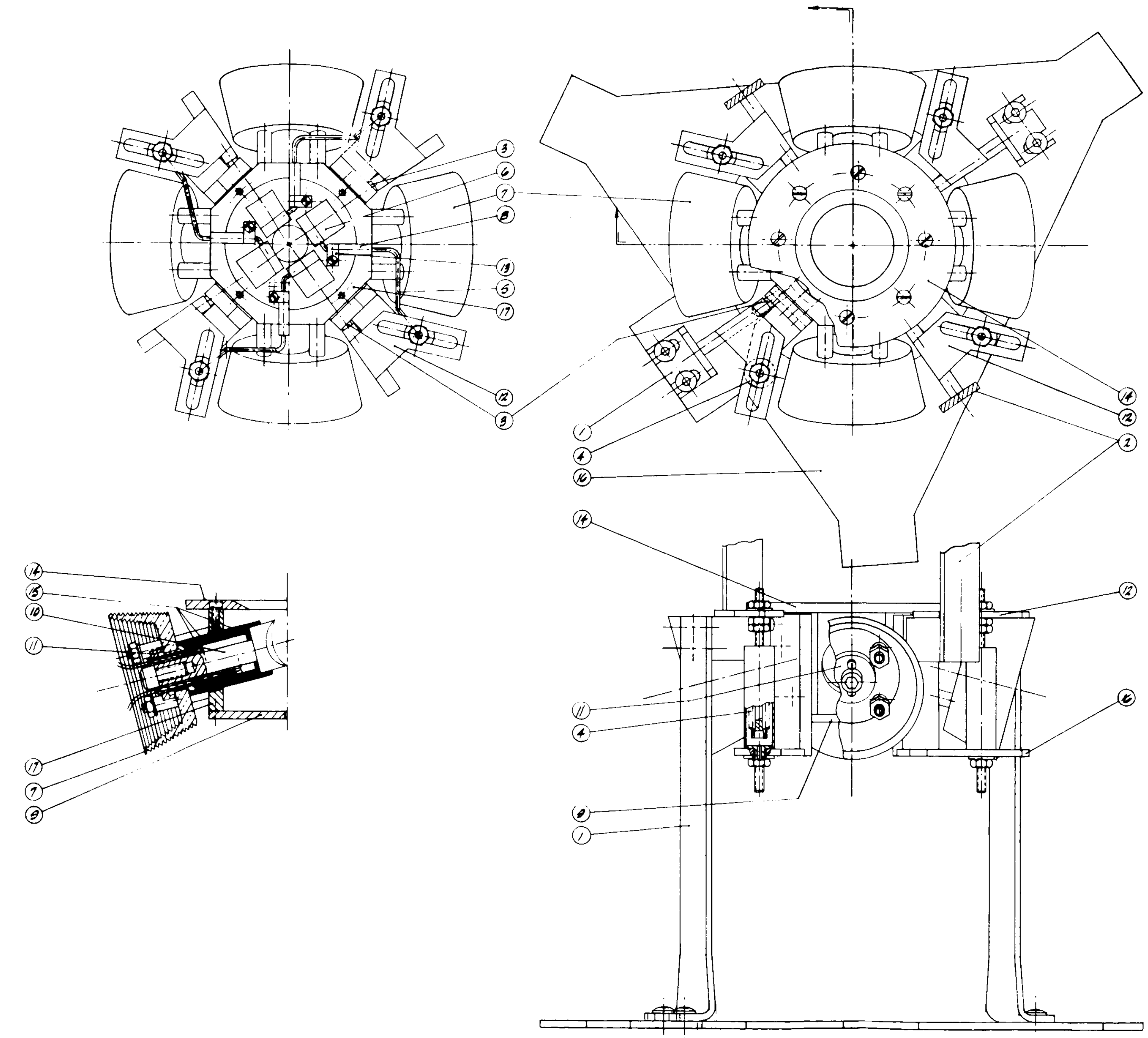
The bellows assembly is fastened into mount brackets by lock screws which facilitate the initial mount adjustments. The elongated slots are provided to an optimization of the torque - stroke characteristics which would depend upon the nature of the disturbances which must be handled or the concentrator mass. These slots would also provide a way of adapting other size bellows assemblies to the existing mount and system, or of adapting the present mount and bellows to other generator-concentrator components of different size and mass.

The sensors are shown as small wedge shaped reservoirs containing mercury sufficient to fill half the sensor volume when the mount is in the balanced position. When the mount rotates the mercury is transferred from the hotter sensor and into its bellows. The opposing bellows forces some of its charge to the cooler sensor. This continues until the mount has rotated a full 5 degrees. At full rotation the heated sensor is deprived of its entire inventory and the mercury recedes into the capillary thereby preventing the overpressure of the bellows assembly.

The damping required for proper system stability is provided by using 10 inches of .005 diameter capillary tube between the sensor and bellows. Since this bore size is as small as can be found any additional damping would have to be added external to the mount assembly. Calculations indicate however that this capillary size should be sufficient to give the factor of 10 required in the previously calculated critical damping.

The sensors are provided with two adjustment features in addition to the possibility of adding shields or applying emissive coatings to alter the temperature characteristics. A small copper holder is used to thermally ground the sensor capillary to the calorimeter body. The length of the path and the conduction between sensor and body may be varied by adjustment in the placement of this copper holder. Also by moving the entire holder and sensor assembly in and out the amount of solar flux intercepted by the sensor at the cavity edge may be controlled to obtain the proper ambient. These features should insure the mount will be compatible with the solar concentrator even in the event the concentrator flux profile is not precisely known before hand.

REVISIONS			
SYM.	DESCRIPTION	DATE	APPROVED



QTY REQD	ITEM NO.	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	MAT'L REFERENCE OR NOTE
4	18		CALORIMETER ELEMENT ASS'Y	—
1	17	818427	CALORIMETER BODY	CRES
1	16	818430	SUPPORT PLATE	CRES
4	15		SHIELDING ASS'Y	MOLYBDENUM
1	14	818422	COVER PLATE	CRES
4	13	818431	CLAMP	COPPER
4	12	818426	HELIOTROPIC MOUNT ASS'Y	—
4	11	818424	TIGHTENING CAP	CRES
4	10	818421	CALORIMETER ELEMENT	MOLYBDENUM
1	9	818425	BOTTOM PLATE	CRES
4	8	818431	POSITIONING BLOCK	COPPER
4	7	818420	RADIATOR	COPPER
4	6	818431	SENSOR	CRES
4	5		CAPILLARY	CRES
4	4	818423	BELLOWS ASS'Y	CRES
4	3	818426	BEARING - FREE FLEX	AISI 420
2	2		CONCENTRATOR SUPPORT	CRES
2	1		CONVERTER-CONCENTRATOR SUPPORT	CRES

LIST OF MATERIALS OR PARTS LIST

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
TOL. ON ANGLES ±
TOL. ON TWO-PLACE DEC. ±
TOL. ON THREE-PLACE DEC. ±
FOUR-PLACE DECIMAL DIMENSIONS WITHOUT TOLERANCE ARE BASIC.

MATERIAL: AS NOTED
HEAT TREAT
WELD OR BRAZE
SURFACE TREATMENT | INSPECTION SPEC. | APPROVAL

DFTM. 56/DJP 5-9-64
CHKD.
APPD.
APPROVAL

TAPCO
A DIVISION OF
THOMPSON RAMO WOOLDRIDGE INC.
CLEVELAND, OHIO, U. S. A.

TITLE: HELIOTROPIC MOUNT & CALORIMETER ASS'Y ON SUPPORT PLATE

NEXT ASSY. (REF.)
CODE IDENT. NO. 59875 | SIZE D | DRAWING NO. 818433
SCALE | SHEET

FIGURE 4.2-1

During laboratory tests of the mount heat will be introduced to the calorimeter element by electron bombardment. A single multi turn tantalum filament is used as the electron gun source. By proper positioning it should be possible to achieve a uniform power introduction to each of the four calorimeter elements. Each element will be monitored for its own fraction of the total bombardment current to permit accurate power measurements to be made for calibration purposes. The sensors include a .110 diameter drilled hole to permit the insertion of a small sheathed heater. These heaters will be used to simulate the solar input power and will be arranged through the use of an electrical switching network to allow a variety of misalignment conditions to be simulated.

Photographs of the principle components and assemblies are shown in Figures 4.2-2 through 4.2-5. The parts which make up the calorimeter elements are presented in Figure 4.2-2. The completed mount assembly exclusive of the bellows-sensor sub-assembly is shown in Figure 4.2-3. Figure 4.2-4 and 4.2-5 respectively show the electron gun assembly and the support structure which will be used to simulate the concentrator mass during the dynamic mount tests.

4.3 Component Specification

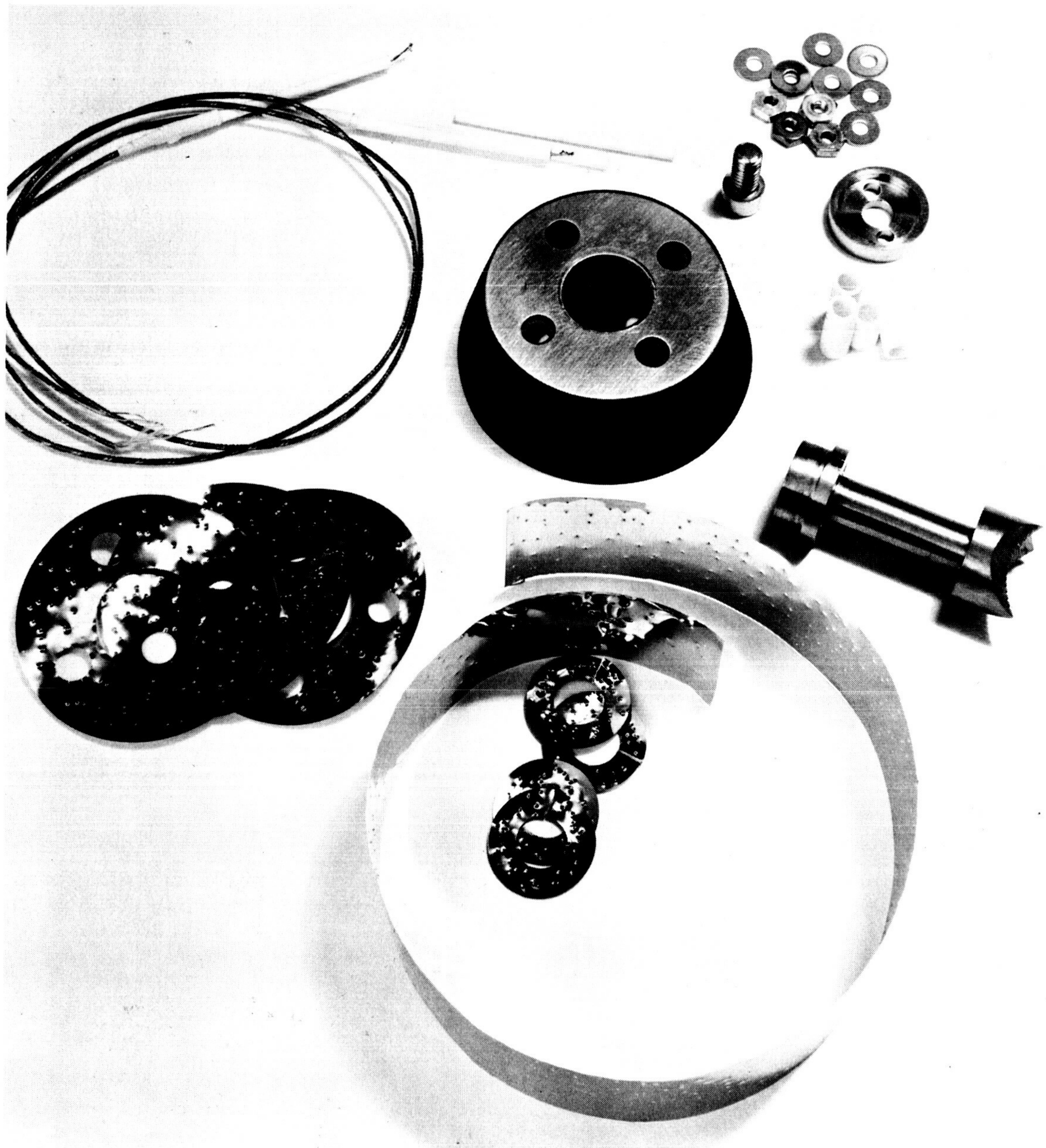
A listing of the specifications for, materials used, and other design operating data concerning the mount and the principle components is presented in the following tables.

TABLE I

DESIGN POINT VALUES

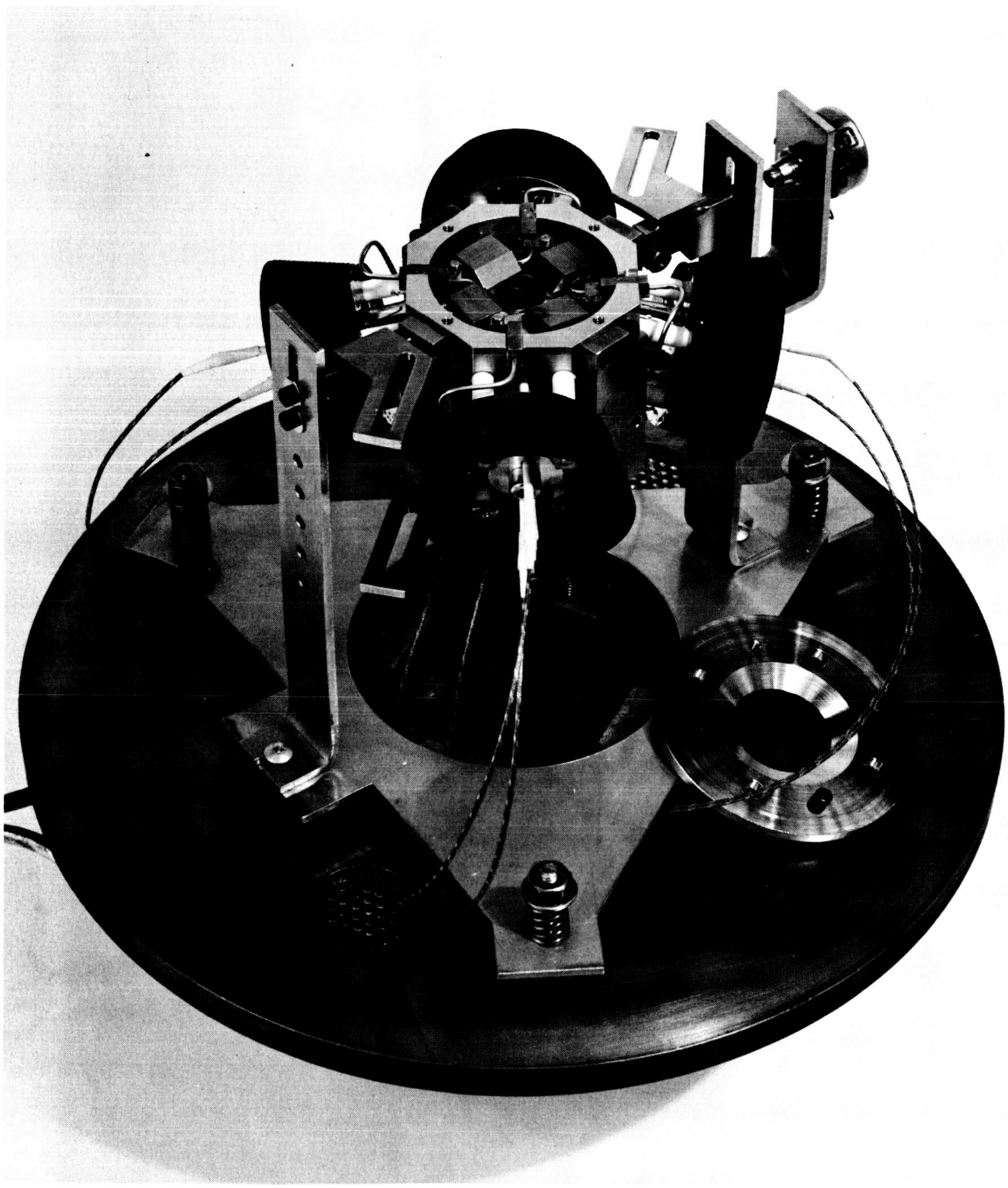
I. Calorimeter Simulator Assembly

1.	Cavity temperature	1700°C
2.	Radiator temperature	490°C
3.	Body temperature	442°C
4.	Calculated ΔT value	680°C
5.	Total cavity power	797 watts
6.	Reradiation loss	161 watts
7.	Element conduction power	151 watts
8.	Cavity absorptivity	.90
9.	Radiator emissivity	.85
10.	Body emissivity	.2



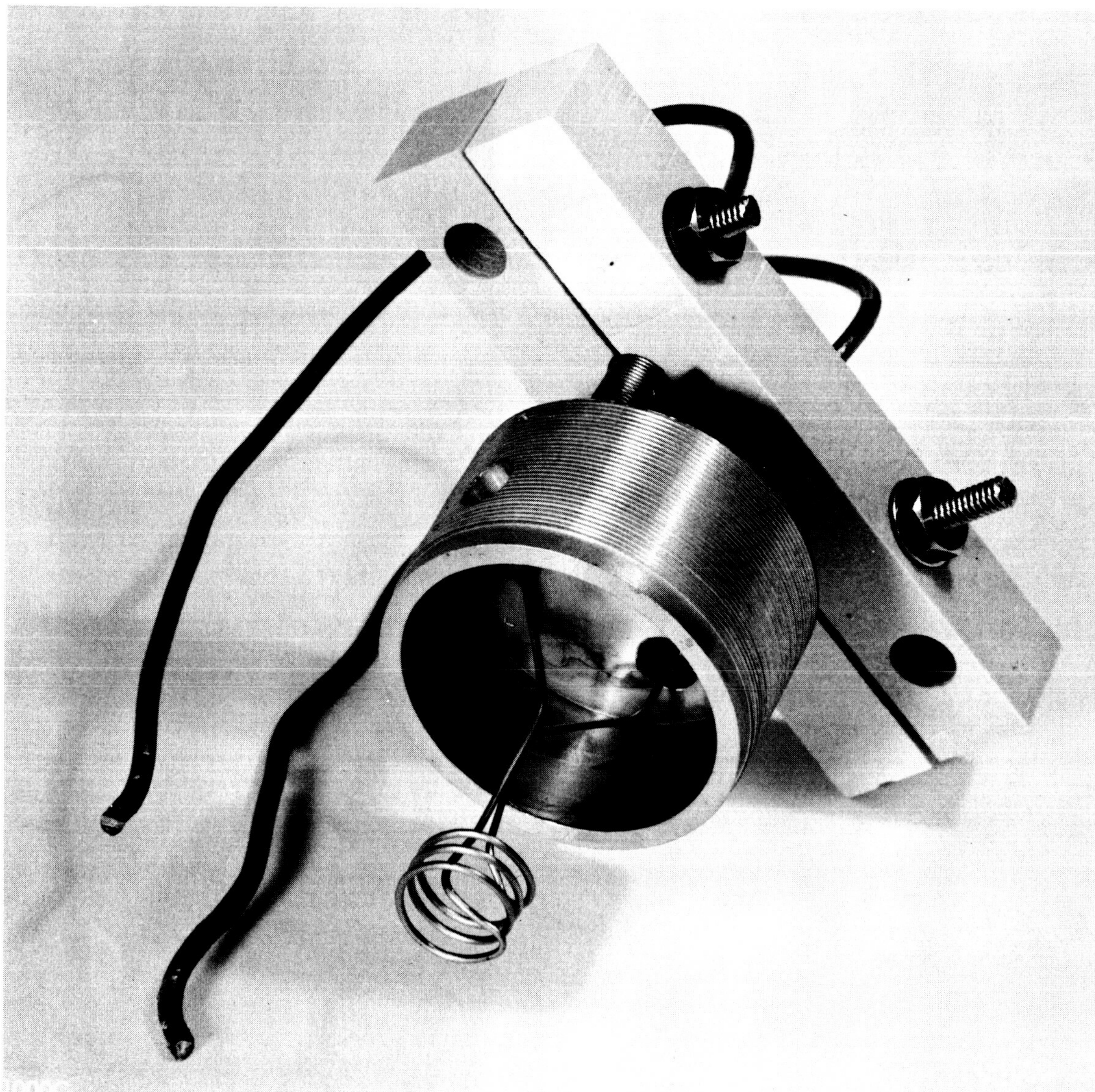
CALORIMETER ELEMENT COMPONENTS

FIGURE 4. 2-2



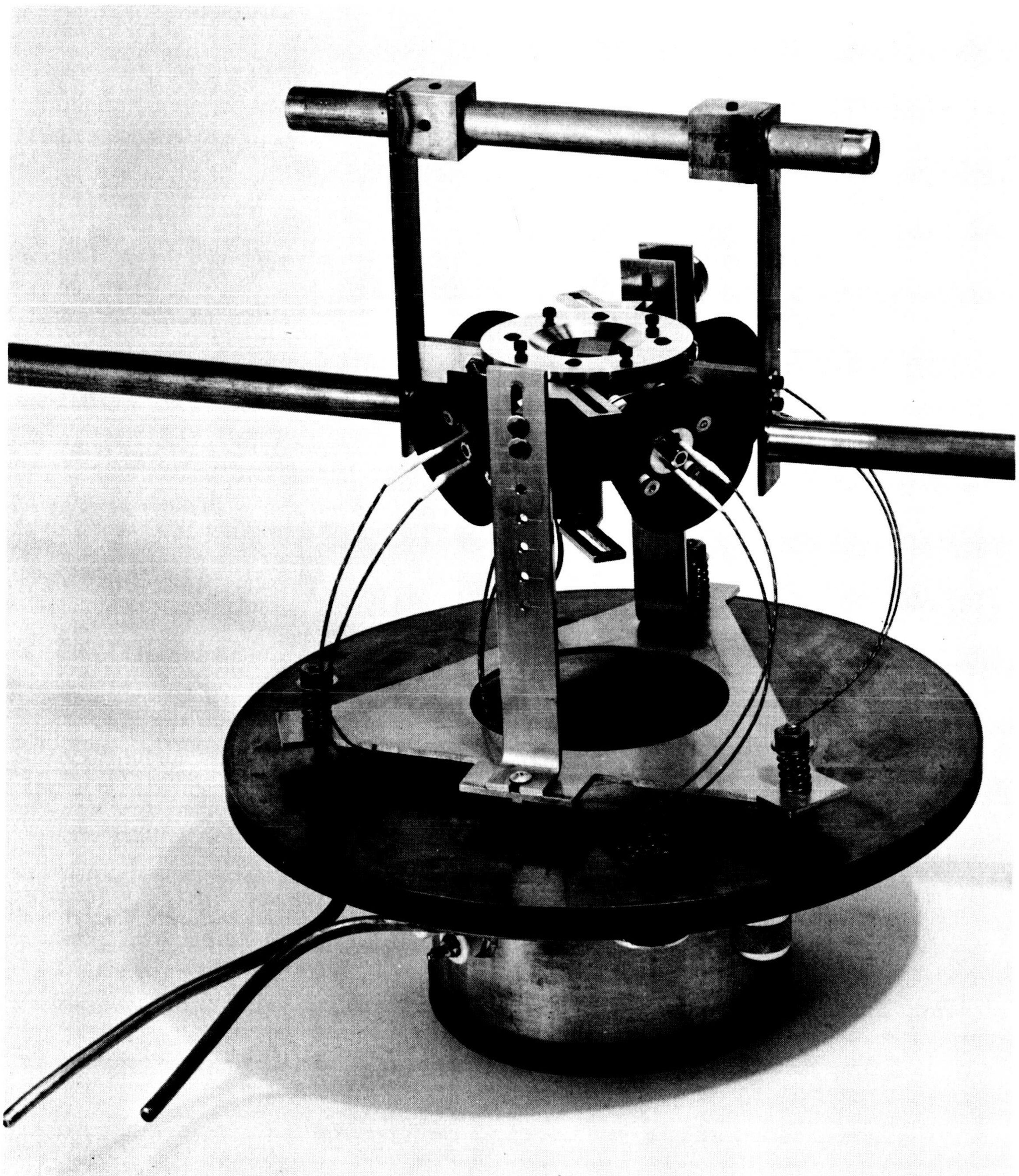
TEST MOUNT ASSEMBLY

FIGURE 4.2-3



ELECTRON GUN ASSEMBLY

FIGURE 4.2-4



MOUNT ASSEMBLY WITH INERTIAL SUPPORT STRUCTURE

FIGURE 4.2-5

TABLE I (Cont'd)

II.	Bellows-Sensor Assembly	
	1. Bellows temperature	400°C
	2. Sensor temperature	572°C
	3. Bearing temperature (max)	400°C
	4. Sensor clamp assembly	442°C
	5. Sensor emissivity (selective)	.05 to .8
III.	Heater and E. B. Gun Assemblies	
	1. EB voltage	600 to 800 volts
	2. EB current per element	.251 to .189 amps
	3. Total EB power	604 watts
	4. Sensor heater input power	4.85 watts

TABLE II

MISCELLANEOUS MOUNT PERFORMANCE CHARACTERISTICS AND PROPERTIES

1.	Maximum motion or rotation	± 6 degrees
2.	Design control motion	± 5 degrees
3.	Maximum allowable residual alignment error	± 12 minutes
4.	Anticipated residual alignment error	± 6 minutes
5.	Anticipated steady state gain (min.)	200 degrees/degree
6.	Frequency response	0 to .1 cps
7.	Mount natural frequency	2.2 rad/sec
8.	Critical damping	76 in#/rad/sec
9.	Bearing load capacity	56#
10.	Minimum cycle life	200,000

TABLE III

MATERIALS

I.	Calorimeter Assembly	
	1. Shaft	Moly
	2. Cavity	Moly
	3. Radiator	Copper
	4. Radiator Coating	Pyromark
	5. Shields	Moly foil
	6. Body	316 S.S.
	7. Cover Plates	316 S.S.
	8. Insulators	Diamonite
	9. Thermocouples	C/A
	10. Studs and nuts	303 S.S.
II.	Electron Gun Assembly	
	1. Filament	Tantalum
	2. Holder	Moly
	3. Holder support insulator	Lava B
	4. Leads	Copper
III.	Heater Assemblies	
	1. Filament	Tungsten
	2. Insulator	Magnesia
	3. Sheath	Nickel
IV.	Bellows Sensor Assembly	
	1. Bellows	347 S.S.
	2. Capillary	347 S.S.
	3. Sensor	316 S.S.
	4. Bellows Housing	347 S.S.
	5. Charging fluid	Mercury
	6. Bearings	S.S.
	7. Support brackets	316 S.S.

TABLE III (Cont'd)

V.	Support structures	
	1. Brackets	316 S.S.
	2. Support Stand	316 S.S.
	3. Misc. Fasteners	Carbon Steel & S.S.

4.4 Proposed Test Program

Four distinct classifications of tests must be accomplished to complete the evaluation of the mount design. This requirement arises from the fact that severe complications result from attempting a test of space qualified hardware under earth bound restrictions. In this program there is a need for carrying out tests where both the vacuum environment of space and the mass characteristics of the system hardware must be simulated. Also a fair test simulation must exclude or compensate for the effects of gravity to completely qualify the test results. To fulfill all of the requirements the following specific test activities must be insluded: 1) vacuum system and instrumentation check out, and calibration, 2) tests to determine all thermal equilibrium and dynamic response characteristics, 3) tests to simulate and evaluate the inertial mount-concentrator characteristics and 4) solar tests to confirm mount gain and response characteristics and verify the compatibility of the mount with the solar test environment of a precision concentrator.

Because of the large concentrator inertias it is impossible to include a mass with similar inertial values within the vacuum test chamber walls. Such a mass would weigh 250 pounds to fit within a 12 inch bell jar and would greatly exceed the bearing load capacity and further complicate the effects of g loading on mount performance. The approach therefore becomes one of performing all thermal equilibrium and thermal dynamic measurements under high vacuum and the inertial or dynamic system response tests outside the vacuum. By careful measurements of all temperatures, and rates of change in temperature for various power input with the mount restrained or loaded with simple weighted lever arms a map of the mount torque and motion is obtained. These characteristics can be compared to the calculated values and computer characteristics to confirm the adequacy of the mount design.

Having obtained the thermal response and torque-motion characteristics under vacuum with the proper temperature environment simulated the mount can be removed from the vacuum for inertial type tests.

Outside the chamber it is possible to apply the weight which simulates the concentrator at a radius of 26 inches. The inertial characteristics are properly simulated and the bearing loads are easily acceptable. The sensors may then be heated to the ambient indicated under vacuum by using oversized electrical heaters and adding more power to overcome the additional heat losses in air. With the sensors forced to the operating temperature in open air the mount torques will be exactly the same as were measured under vacuum. The interaction of the mount and concentrator mass simulator can be observed and recorded as a function of forced sensor temperature variations. Again the response characteristics can be compared with the computer program results. Having monitored and recorded the relations between sensor excitation and mount movement for various types and frequencies of disturbances the complete mount performance can be determined by combining the results of both vacuum and air tests.

Having obtained all pertinent mount characteristics in the laboratory it will be possible to proceed with the solar test activity. Again because of the need for a vacuum enclosure the concentrator in the tracker cannot be connected directly with the mount assembly. Also to do so would be useless since the tracker mirror weighs several hundred pounds. The results of applying flux unevenly to the sensors can be determined indirectly however. By starting with the concentrator corrently aligned and the mount properly located in the focal plane the ambient operating conditions can be established. If at this point a known alignment error of several minutes is introduced in the tracker orientation system the sensors will be heated unevenly and a torque developed in the mount actuators. By allowing the mount to rotate until it reaches a new torque equilibrium point at x degrees the mount gain can be calculated. The response can also be obtained from recordings of this rotation. By introducing a sinusoidal disturbing signal in the tracker the dynamic response of the mount can be obtained for several frequencies and again compared with the previous computer results.

Having completed all three test series all mount characteristics will be known and it will have been demonstrated that the mount is properly designed to respond to an actual solar test environment. A summary of the overall proposed test program is presented as follows.

The instrumentation available in the calorimeter mount assembly which will be used to facilitate the testing is as shown in Figure 4.4-1.

Explanation of Instrumentation

Symbol or point	Description
1 - 8	thermocouples mounted in diode simulating elements
9 - 12	thermocouples mounted in sensors
13 - 16	thermocouples mounted in radiators
17	thermocouple in calorimeter body
18	thermocouple in base plate

INSTRUMENTATION ARRANGEMENTS

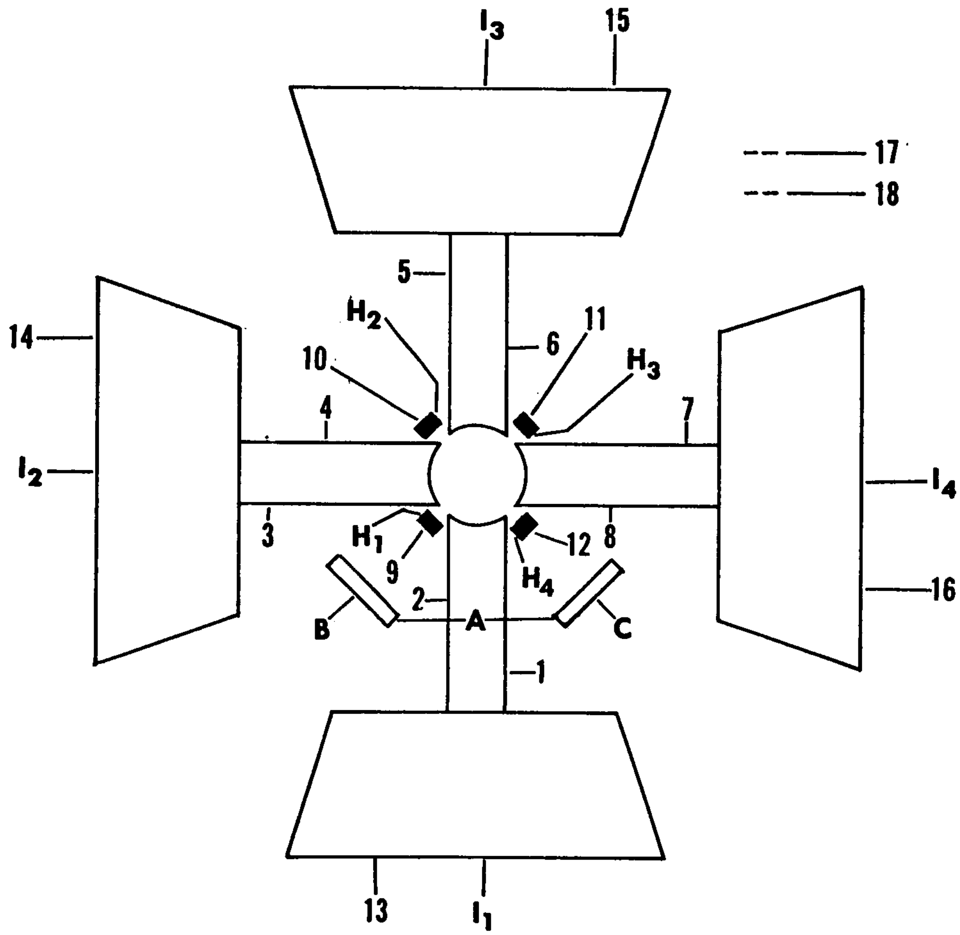


FIGURE 4.4-1

H_1, H_2, H_3, H_4	sensor heaters
I_1, I_2, I_3, I_4	respective EB current leads
A	motion transducer input leads
B	X-axis transducer output
C	Y-axis transducer output

TEST SUMMARY

I. Vacuum System and Instrumentation Checkout

1. The completed assembly will be pumped down and leak checked to insure a tight system.

2. Having reduced system pressure to below 10^{-5} mm hg the high voltage will be applied to insure proper isolation of the calorimeter and electron gun assembly.

3. The high voltage will be reduced and the bombardment filament will be heated to produce small emission currents. All thermocouples will be noted for proper response, and the bombardment current distribution to each calorimeter element determined. A measure of stray bombardment current to dummy sensors initially installed in the calorimeter will also be made. Corrections for distribution, sensor interception, or other improper conditions will be made.

4. The bombardment power will be raised slowly until the design power level is reached. The period required will be determined by the rate of outgassing. Vacuum rise will be limited to 10^{-4} mm hg.

5. A survey of all temperatures which result from full power input will be made. Assuming all values are reasonable the calibration of the calorimeters will begin.

6. Each calorimeter will be calibrated to determine the variation of ΔT with power input. Power input will be measured in terms of bombardment current. Characteristics curves will be prepared for each element. Elements shall be adjusted as required to provide uniform characteristics. These adjustments may be made by altering the shaft dimensions or adding shields or emissive coatings in the radiator or other areas. The cavity temperature will also be monitored with an optical pyrometer to insure any corrective measures taken are appropriate in attaining the 1700°C cavity operating temperature design point.

7. The proper location of shielding, coating, and thermal grounding of the sensor will be accomplished by trial until it is satisfactorily determined that the sensor ambient temperatures are correctly established at the design value.

At this point the preliminary test are concluded and the mount evaluation will begin.

II. <u>Mount Vacuum Tests</u>

1. With the bellows-sensors assembly in place and the calorimeter heated and under vacuum the sensors will be monitored for temperature. Adjustments will be made to obtain a proper balance in opposing sensors at the design temperature (959°F without the solar input).

2. Variations in sensor temperature as a function of calorimeter power and temperature will be recorded.

3. The sensors will be heated by the electrical elements until the design solar power input is simulated. Sensor temperature at the design point and at solar power inputs greater than and less than the design value will be measured. This test will be repeated until a sufficient data is available to plot a curve of sensor ambient temperature versus solar power input with the calorimeter operating at design conditions.

4. With the sensors and calorimeter operating at design conditions, step changes in input sensor power will be introduced. The time rate of change in sensor temperature recorded and the new equilibrium temperatures noted. This will be done for several power inputs. Sufficient data will be obtained to determine sensor thermal response and the equilibrium temperatures that result for solar power inputs above or below the design point level. The mount will be unloaded and unrestrained during these tests.

5. In conjunction with test 4 the motions which are induced in the mount by the changes in sensor power input and temperature will be recorded. From this data and data from subsequent tests the mount torque motion characteristics will be determined.

6. The mount will be fitted with an unbalanced load which will cause an initial rotation of the assembly. The mount and calorimeter will be heated to the design point and the sensors subjected to a gradually increasing power input unbalance. This unbalance will be increased until the mount has overcome the load unbalance and restored the assembly to the level or "oriented" condition. This test shall be repeated using several loads. From data obtained on sensor temperature, power input, and load torque, a plot of mount restoring torque as a function of sensor power input unbalance or "orientation" error may be developed. These tests will be conducted to provide data simulating orientation errors introduced in three planes through the mount axis.

7. An attempt will be made to introduce sinusoidal power variations in the sensors. The angular response of the mount as a function of the disturbing frequency will be recorded. From this data a plot of mount gain and response will be obtained for a known disturbing error signal. This test will be repeated for several ambient sensor temperatures to provide a complete performance map. This test is suitable for obtaining sensor response characteristics only since no inertia other than that of the mount is involved.

III. <u>Inertial Tests</u>

1. The mount will be removed from the vacuum system, stripped of the electron gun, and fitted with a balanced inertial mass assembly to simulate the solar concentrator. The sensors will be elevated in the calorimeter assembly and fitted with larger heaters.

2. The sensors will be forced to their design operating temperature in open air by the heaters. Small orientation error simulating sensor temperature variations will be induced and the motion of the mount and the inertial assembly it supports will be recorded.

3. The procedure in 2 above will be repeated for step and sinusoidal type sensor power variation. This will be done in three planes 45 degrees apart through the mount axis. Also inertial loads simulating 7.5, 10, 15, and 20 pound concen-centrator assemblies shall be tested.

4. Mount natural frequency and the effective damping of the bellows capillary system shall also be determined for the four inertial masses simulated in 3. This shall be accomplished by manually loading and releasing the mount assembly. The determination of the mount characteristics will then be made by analysis of the oscillation decay trace from the motion transducers.

IV. <u>Solar Tests</u>

1. The mount will be reassembled as it had been for the vacuum tests except for the omissions of the heaters and gun assembly. In this installation of the calorimeter the original support brackets will be removed and the assembly rigidly suspended from the calorimeter body. A pair of concentric rings will be added to tie together opposing bearing-bellows assemblies. With this arrangement the mount calorimeter will always be aligned with the tracker concentrator axis. A misorientation of the tracker will then provide an unbalanced heat input to the sensors which will result in a rotation of the newly installed rings. The motion of these rings will be read out by the transducers and mount gain may be determined as a ratio of tracker error to mount rotation.

   The mount will then be installed on the solar tracker with the environmental chamber enclosure. The system will be evacuated and leak checked and proper operation of all instrumentation confirmed.

2. The concentrator and calorimeter cavity will be optically aligned using a ray trace to the cavity from several points on the otherwise shielded concentrator surface. The environmental chamber will be adjusted to direct all such rays into the cavity with the tracker oriented. The chamber shields will be closed and the concentrator shields removed. The chamber shields will be slowly opened and all internal calorimeter and sensor temperatures monitored. Care will be taken to prevent sensor temperature from exceeding 1300°F. Minor adjustments will be made by means of the jack screws to better place the sensors with respect to the solar flux cone if required. If this adjustment is not sufficient the assembly will be adjusted internally to establish proper sensor temperatures under solar operation.

3. With design conditions established under solar powered operation a small error will be introduced in the tracker orientations. Sensor temperature, calorimeter temperatures and mount ring motions will be recorded. A range of errors will be introduced in three planes and all data recorded. Steady state gain will be determined from this data.

4. Small step and sinusoidal errors will be introduced and the pertinent data recorded as in 3 to provide dynamic sensor temperature characteristics.

5.0 COMMENTS AND WORK PLANNED

The progress on this program has been very satisfactory in most respects. The review of actuation concepts has shown that there are several mechanisms which might be worthy of development as heliotropic devices. The bimetal helix concept in particular may prove quite excellent for an orientation system which does not require rapid response. Also the use of secondary optical systems as part of the sensor input mechanism has yet to be explored and may yield a group of orientation devices suitable for solar collection systems of other than the precision variety.

The use of the calorimeter to simulate a thermionic generator in the mount assembly may be considered somewhat elaborate and unnecessary but such is not the case. Since it is essential to prove the mounts capability under typical system operating conditions the entire environment must be simulated as faithfully as possible. Only by building the mount actuation hardware around such a calorimeter and testing it as part of an operating generator simulator can the proof of performance be accepted.

The complexity of the mount configuration and the overall test program is somewhat greater than was originally anticipated. The amount of care and effort which will be required for the successful completion of the program will also be greater, but the performance potential of the prototype mount more than justifies this requirement.

The computer study of the bellows concept indicated this device should have performance characteristics far superior to those experienced or calculated for the bimetallic types. If the mount can be developed to the point of matching the computer results there should be little doubt that heliotropic devices will be of great value in future solar power systems. The problems of trying to fully develop this mount within the few months allotted for that purpose in this program are great. The approach taken is sound but there are many obstacles any one of which could prevent a wholly successful program.

In the fabrication area it must still be demonstrated that the bellows assemblies can be properly evacuated and charged with mercury. The problem of filling the assembly is greatly aggravated by the location of the very small damping capillary between the sensor and bellows and the very irregular shape of the bellows structure. The present plan is to evacuate both the sensor and bellows through two large 1/8 diameter pinch off tubes and to backfill into the bellows reservoir space. This will in part reduce the problem of trying to pump through the capillary and offer a reasonably hard vacuum for the initial mercury charge. A heating cycle under vacuum and the manual stroking of the bellows will be used to attempt to remove all traces of entrained air. After the fill is complete the bellows tube will be crushed and welded and the proper amount of inventory established by deflecting the bellows to force mercury throughout the capillary sensor portion. The sensor tube is then pinched off to complete the charging. Following this charging procedure the assemblies must be installed and very carefully preset provides exactly the right amount of motion in the mount. The approach is straight forward but its accomplishment may be very difficult.

The proper operation of the mount is also very dependent upon being able to establish the sensor operating point at very near the 1059°F design value. The heat balance associated with the attainment of this temperature is very complicated and our present calculation are only first order approximations. The real proof of the mount design will be in demonstrating there is enough flexibility in the sensor mounting hardware to accommodate for the errors in our approximations. Even after the proper design temperatures have been established under laboratory conditions there will still be a final test of design compatibility with the TRW solar tracker rig. In spite of the fact that considerable data is available regarding the concentrator flux profile and the probable solar energy interception by the sensor, there is still much concern over the effect of reflected energy from the cavity and even of sizeable distortions in the flux profile at the aperture edge. The latter being due to gravitational loading or uneven support of the concentrator. These factors do not yield to analysis and therefore will be resolved only by actual tests later in the program.

At this point the test mount is complete except for final assembly and charging of the bellows-sensor subassemblies. Some preliminary tests have already been conducted and more will be undertaken as the program continues. Some modifications in the form of reshaping and shielding of the electron gun filament have been made with good success. Changes in the method of supporting and thermally grounding the sensors have also been made and are being readied for retest. If these modifications are sufficient the preliminary tests and calibrations will be carried out. The evaluation of the mount characteristics shall proceed according to the test program outlined in this report at the conclusion of these preliminary tests.

The results of all test activities including an evaluation of the mount in terms of its state of readiness for a space test will be presented in a final report. Recommendations for further development work, modifications of the basic mount design, or other innovations shall be included.